Lappeenranta University of Technology

LUT School of Energy Systems

Degree Programme in Energy Technology

Master’s Thesis

Vesa Vartiainen

SCREENING OF POWER TO GAS PROJECTS

Examiners:	Professor, D.Sc. Esa Vakkilainen
	Docent, D.Sc. Juha Kaikko

ABSTRACT

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Keywords: power to gas, renewable energy, energy storage, electrolysis, methanation

The purpose of this thesis was the screening of power to gas projects worldwide and reviewing the technologies used and applications for the end products. This study focuses solely on technical solutions and feasibility, economical profitability is excluded.

With power grids having larger penetrations of intermittent sources such as solar and wind power, the demand and production cannot be balanced in conventional methods. Technologies for storing electric power in times of surplus production are needed, and the concept called power to gas is a solution for this problem.

A total of 57 projects mostly located in Europe were reviewed by going through publications, presentations and project web pages. Hydrogen is the more popular end product over methane. Power to gas is a viable concept when power production from intermittent sources needs to be smoothed and time shifted, when carbon free fuels are produced for vehicles and when chemical industry needs carbon neutral raw materials.

TIIVISTELMÄ

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Avainsanat: power to gas, uusiutuva energia, energian varastointi, elektrolyysi, metanointi

Diplomityön tavoitteena oli kartoittaa power to gas –projekteja maailmanlaajuisesti ja arvioida niissä käytettyä teknologiaa ja lopputuotteiden käyttötarkoituksia. Tämä työ käsittelee pelkästään teknisiä ratkaisuja ja niiden toteutettavuutta, taloudellinen kannattavuus on jätetty tarkastelun ulkopuolelle.

Kun sähköverkkoihin liitetään yhä enemmän ajoittamattomia tehonlähteitä kuten aurinko- ja tuulivoimaa, sähkön kysyntää ja tuotantoa ei voida enää tasoittaa perinteisin menetelmin. Power to gas –konsepti on yksi ratkaisu tähän ongelmaan.

Työssä kartoitettiin kaiken kaikkiaan 57 projektia käymällä läpi julkaisuja, esitelmiä ja projektien Internet-sivuja. Projekteja tarkasteltaessa kävi ilmi että vety on metaania suositumpi lopputuote. Power to gas –konsepti on kannattava ratkaisu kun ajoittamatonta sähköntuotantoa halutaan tasoittaa ja siirtää ajallisesti, kun liikennekäyttöön halutaan tuottaa hiilineutraalia polttoainetta ja kun kemianteollisuus tarvitsee hiilineutraaleja raaka-aineita.

PREFACE

I would like to thank Professor Esa Vakkilainen for providing me the opportunity to do this thesis. This work is part of Neo-Carbon Energy project, and I’m grateful for Tekes for funding the project and making this kind of research possible.

Throughout the time I have spent in Lappeenranta University of Technology, the studies have always been oriented in practical applications, making the studying very interesting and motivating.

A special thanks to my fiancée and daughter for the support in everything.

Vantaa, 16.5.2016

Vesa Vartiainen

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ABBREVIATIONS

CHP	Combined Heat and Power
SNG	Synthetic Natural Gas, Substitute Natural Gas
P2G	Power to gas
P2X	Power to product
AEC	Alkaline Electrolysis Cell
AEL	Alkaline Electrolysis
PEM	Proton Exchange Membrane, Polymer Electrolyte Membrane
PEMEC	Proton Exchange Membrane Electrolysis Cell
SOEC	Solid Oxide Electrolysis Cell
HHV	Higher Heating Value

1 INTRODUCTION

1.1 Background

The renewable energy production is increasing worldwide. The European Commission, for example, has set a target for producing 20 % of its final energy consumption renewably by 2020. Various reasons for promoting renewable energy production include the depletion of fossil fuel reserves, several nations’ desire for independence from imported energy and impact of the fossil fuels on the greenhouse gas emissions and climate change. Various alternatives for fossil fuels are nuclear energy and renewable sources, such as biomass, hydro, solar and wind power. Hydro power is very predictable, cheap and easily adjustable source of power, but the additional resources compared to current constructed ones are limited. Solar and wind energy have large unconstructed resources, and their shares of total energy production have grown rapidly in recent years [1, p. 11].

The relevant problem with solar and wind power is that the power production cannot be adjusted to correspond the electricity consumption. With conventional fuel-based power generation the production balancing is relatively simple. In the period of decreased power consumption, a number of power plants connected to the grid decrease their power output or shut down their production completely, resulting in conserved fuel to be used later. The same principle applies to hydro power, where water can be accumulated up to certain level in the upstream reservoir. Solar and wind power are intermittent in nature, and the peak production rarely meets the moments of peak demand. Unlike fuel in traditional power plants, wind or sunshine cannot be conserved for later use. Limiting the power output of these plants means losing potential production.

In most power grids of today, the load balancing is carried out typically by adjusting more easily adjustable power generators, as described above. This is an effective method in grids which have a low penetration of solar and wind production, but the more the penetration reaches, the more relevant becomes adjusting the production from these sources.

1.2 Objectives

Power to gas is a concept in which surplus electric power is converted into a chemical media which can be stored, distributed and used in times of electricity deficit. It is relatively new method of storing energy, and in addition to pure power production it can be used to produce carbon neutral fuels for vehicles and raw material for chemical industry. The purpose of this thesis is to review recent, significant and well documented projects and asses the current state and feasibility of the technology and sort out applications for the end products of these facilities. Economical viability and potential productivity is excluded, the focus being solely on the technological feasibility and applications.

1.3 Structure of the thesis

Chapter 2 describes the alternative methods for energy storage, and introduces the concept of power to gas in this context.

In chapter 3 possible products of power to gas processes are described. Different processes which can be included in the concept are explained and general values of efficiencies are given.

Chapter 4 presents the list of projects reviewed. The projects are studied by going through publications, presentations and project web pages.

The findings are discussed in chapter 5.

Chapter 6 concludes the thesis and summarizes the essential findings.

2 ENERGY STORAGE

In the developing of an energy grid that depends highly on solar and wind energy, storing the energy in surplus production periods is a crucial factor. Storage methods for energy can be divided into three categories: mechanical storage, electricity storage and chemical storage. Most used and well-known examples of each category are presented in the next sections, with the focus thereafter being on chemical storage.

2.1 Mechanical energy storage

Pumped hydroelectric storage is the most used energy storage method today. In this concept, water from a reservoir is pumped during off-peak hours into another reservoir at a higher elevation. In times when electric power is needed, water is released back to the lower reservoir through turbines and power is generated. These systems have typically very high efficiency of over 80 % and they can have large capacities of long-term energy storage. The pumped hydro storage system can only be built into locations where both high elevation difference and large area for reservoirs are available, hence further commissioning of this type of facilities relatively limited [2].

Flywheels store the electric energy in mechanical spinning motion. In times of cheap electricity prices or surplus production, a flywheel is accelerated by an electric motor drawing power from the grid. When the grid needs energy or when the price is high enough, the operation is reversed and the motor will function as a generator, braking the flywheel’s spinning and producing electric power to the grid. Flywheels are used today in frequency regulation applications, as the energy can be extracted almost instantly without delay. Capacities of these systems are relatively low, largest of them are in the scale of a few kWh’s, hence this type of technology is not suitable for long-term or large scale energy storage [3].

In the compressed air energy storage, commonly referred to as CAES, air is compressed using electric energy and stored in a container. The size of the container depends on the application. In smaller scale such as the system of pneumatically driven tools or a vehicle, a conventional pressure tank is sufficient, but when storing surplus grid energy underground caverns are needed to provide for the large capacity and power. When the storage is discharged, the pressurized air is heated and expanded in a turbine. The heating is typically done by combusting natural gas, which resembles a conventional gas turbine generator with the exception of the separated compression phase. Research work is done to find a way to recover the compression heat and further improve the efficiency, up to 70 % [4].

2.2 Electric energy storage

Electric power can be stored directly in capacitors and electrochemically in batteries. Capacitors, referred sometimes to as supercapacitors or ultracapacitors, store the energy in the form of electrical charge at the surface of their electrodes. Capacitors can charge and discharge very quickly, and due to the practically negligible degradation their lifetime is very long and maintenance free. Capacitors have a high self-discharge rate which makes them unsuitable for long term energy storage.

Batteries store the energy in a reversible electrochemical reaction. Various types of conventional batteries exist and are used, such as lead, nickel, sodium and lithium based. Different types of batteries have slightly different characteristics, but common drawback is the limited lifetime and number of charge-discharge –cycles. Shared drawback with capacitors is the limited overall capacity, as battery or capacitor systems are composed of numerous cells. Direct storage of electricity is currently used in smaller scale in local energy systems, frequency regulation of the grid and uninterruptible power supplies. Electricity storage has potential in peak shaving applications, but current technologies seem unable to store energy for longer periods of time [5; 6; 7, p. 39-43].

2.3 Chemical storage – power to gas

In chemical storage, electric power is used in an electrochemical process or combination of electrochemical and chemical processes to produce synthetic fuel. Feedstock materials are low energy content and the end products are of higher energy content, due to energy input in the form of electricity, with certain losses. The relatively high energy content (compared to pumped hydro or compressed air), ability of long term storage due to the stability of the chemical medium and the possibility to produce carbon-neutral fuel are factors that make this method of energy storage very interesting. The stored energy can also be transferred to other applications such as transport sector, where alternatives for fossil fuels are desired [8, p. 442].

The concept where electric power is converted into chemical potential energy of a gaseous medium is called *power to gas*. The end products of the energy conversion process are generally hydrogen and methane. Methane produced this way is also called *substitute natural gas*, as it has equal properties with natural gas. In following sections hydrogen as a fuel, its applications and production methods are described. In section 3.5 methane and its production in power to gas-concept is described. Detailed depictions of methane as a fuel is neglected due to the fact that natural gas is already a well established fuel and the methane produced via power to gas –process can be directly used in existing natural gas applications.

Power to gas enables the integration of electric and gas networks. Whenever surplus electric power is available (very low or negative electricity prices), it can be converted into hydrogen or methane gas and stored and distributed in the gas network. In times of electricity deficit (high electricity prices) gas can be used to generate electricity in traditional combustion plants or fuel cells.

3 POWER TO GAS PRODUCTS

3.1 Hydrogen fuel

Hydrogen is the first element in the periodic table. Traces of it in the form of gaseous H_2 are found in small concentrations in the atmosphere, but for industrial purposes it has to be produced from raw materials such as natural gas or water. Hence it is not considered to be an actual energy source like natural gas, but an *energy carrier*, much like electricity. The energy density of hydrogen is not particularly high. In respect to mass, the lower heating value of hydrogen (120 MJ/kg) is higher than that of natural gas (50.1 MJ/kg), but that is due to the very light weight of the hydrogen molecule. The lower heating value relative to the volume of the fuel is technically more significant, and the value of natural gas (36 MJ/Nm³) is over three times the value of hydrogen (11 MJ/Nm³) [9].

3.2. Hydrogen applications

Chemical industry is currently the largest user of hydrogen. Among many products, hydrogen is used to produce ammonia and methanol, and it is also an important component in the refinement and desulfurization of oil [10, p. 2051; 11].

The chemical potential energy of hydrogen can be converted to power and heat in a fuel cell or in a traditional gas combustion engine. When burned with oxygen, the combustion process produces water vapor, which is not considered as an emission. Combustion in air produces small amounts of nitrogen oxides depending on the burning conditions. Hydrogen can therefore be considered as a zero-carbon and low-emission fuel when burned in gas engine. Hydrogen is typically burned in a combustion engine in a gas mixture with natural gas (Chubut, GRHYD), although there are projects in which pure hydrogen is combusted (Utsira). Co-firing hydrogen with natural gas is also the case when it is injected into the natural gas grid.

The combustion reaction for hydrogen is described in equation 3.1.

$$H_2 + \tfrac{1}{2}\, O_2 \rightarrow H_2O + energy \qquad (3.1)$$

Reduction and oxidation reactions in a fuel cell are described in equations 3.2 – 3.4. Electric current is caused by the exchange of electrons e^-. In addition to electron flow (electric power), heat is also released.

$$Anode\colon\ H_2 \rightarrow 2H^+ + 2\,e^- \tag{3.2}$$

$$Cathode\colon\ O_2 + 4\,e^- \rightarrow 2\,O^{-2} \tag{3.3}$$

$$Chemical\colon\ 2H^+ + O^{-2} \rightarrow H_2O \tag{3.4}$$

Hydrogen has for many years been expected to make a breakthrough in mobility applications, in particular as a fuel for fuel cell vehicles. A number of promising experimental projects in mobility applications have been carried out, and the infrastructure of hydrogen dispensing network is increasing at a promising pace. A significant number of the projects presented in later sections dispense all or part of their produced hydrogen in a hydrogen fueling station [12].

It is possible to utilize hydrogen in the methanation process, the second main process chain in power to gas concept. In the methanation carbon source is combined with hydrogen to form methane. This process is presented in more detail in section 3.5. The synthetic natural gas can be distributed and used by standard natural gas applications (power generation, vehicles and appliances) without modifications, bypassing many of the problems associated with the use of gaseous hydrogen.

3.3 Hydrogen storage

In most hydrogen applications, hydrogen is stored in high pressure gas cylinders. Higher storage pressures provides better energy content by volume, but causes loss in the overall efficiency as more compression energy is needed. In the power to gas projects presented in later sections, storage pressures vary in the range from 6 to 950 bar. Long term storage in underground caverns is being researched, but no projects have yet been realized. Regarding to the power to gas concept, hydrogen storage and distribution in the pressurized gaseous form via the natural gas grid is the primary method. Maximum concentration that have been tested in local natural gas grids are 20 % of hydrogen (Ameland and GRHYD) [10, p. 2050; 13, p. 1374; 14].

Hydrogen can be stored in a liquid form in a cryogenic container in 20 K or -253 °C. This method of storage is technically challenging because of leakage prevention and major insulation, and significant energy losses are associated from the cooling of the hydrogen. Liquid hydrogen is used in special applications such as rocket propellants, and it is not a plausible storage method in power to gas concepts [13, p. 1374; 15].

Hydrogen bonds with metals by forming a solid hydride. The hydrogen is discharged by adding heat to the storage system. Magnesium hydride (MgH_2) is the most used medium in solid state storage. Hydrogen stored in a solid state eliminates the problems and safety issues of pressurized gas, but due to early stage of development various challenges exist. Difficulties have been reported in maintaining required temperatures, and the storage systems are also quite massive. A system of 215 kg is needed for storing 3 kg of H_2, when the same amount of gaseous hydrogen stored in a pressure tank of 350 bar would only need a system weighing 45 kg. The solid state hydrogen storage is experimented with in three projects presented later (Cottbus, INGRID, El Tubo) [10, p. 2050-2051; 16, p. 20].

3.4 Electrolysis

In the industrial production of hydrogen the steam reformation using natural gas as raw material is the dominant and lowest cost method. In the United States, 95 % of hydrogen is produced this way. However, using water as the source of hydrogen and electricity from renewable power generation would make the process carbon neutral and eliminate the need for fossil raw material [17].

The electrolysis of water is a process in which electric power is used to split water into hydrogen and oxygen, as described in equation 3.5.

$$2\,H_2O(l) + \ energy = 2\,H_2(g) + O_2(g) \tag{3.5}$$

There are three main methods of electrolysis in use today, all of them have the same overall reaction of equation 3.5. More detailed descriptions and characteristic features of individual electrolysis methods are explained in following sections.

3.4.1 Alkaline electrolysis

The most used and developed electrolysis technology is alkaline electrolysis, referred as AEL or AEC. In alkaline water electrolysis, direct current is passed between electrodes in a water-based solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). A membrane is placed between anode and cathode to separate the hydrogen and oxygen product gases. A hydroxide ion (OH^-) is passed through the membrane to transport the electric charge and closing the circuit. A schematic of the alkaline electrolysis is presented in figure 1.

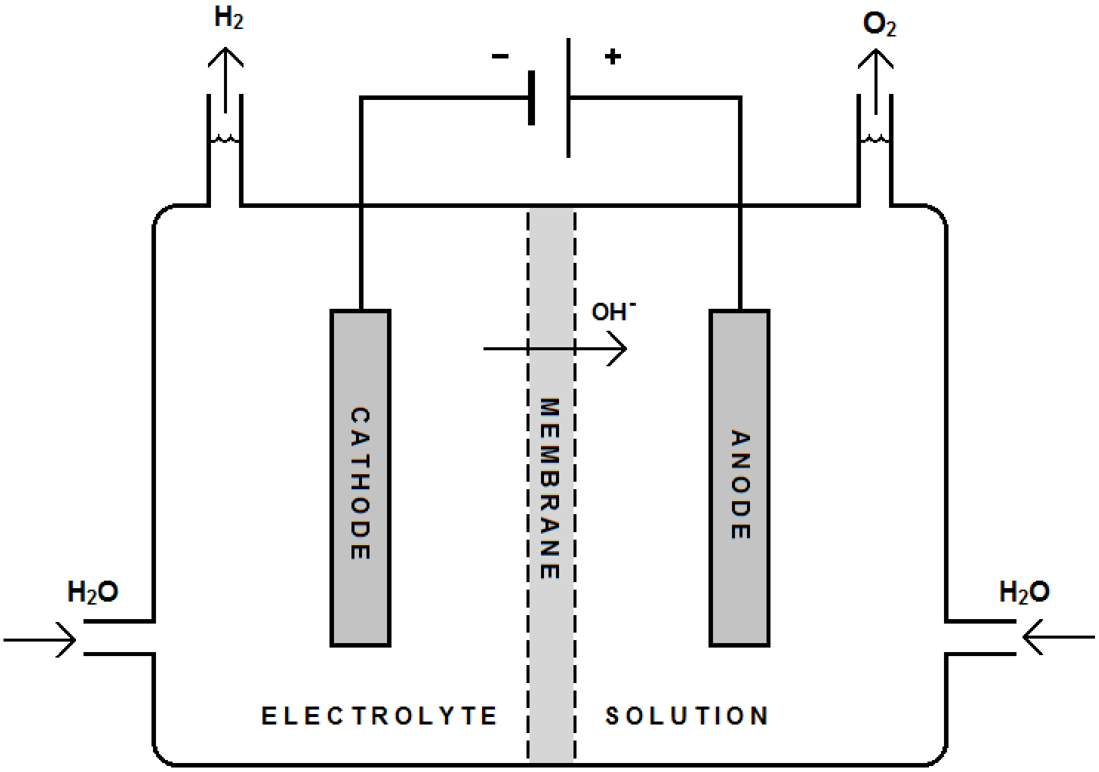

Figure 1: Working principle and mass flows of alkaline electrolysis.

The electrochemical reactions occurring in cathode and anode are presented in equations 3.6 and 3.7 respectively. As it can be seen, one water molecule is consumed during a cathode-anode-reaction.

$$2\,H_2O + 2e^- \rightarrow H_2 + 2\,OH^- \tag{3.6}$$

$$2\,OH^- \rightarrow \frac{1}{2}\,O_2 + H_2O + 2\,e^- \tag{3.7}$$

Lehner et al describes typical efficiencies of alkaline electrolyzers to be 60 – 80 %, based on the HHV of gaseous H_2. Alkaline electrolyzers can be operated on partial loads starting from about 20 %, but the product quality and efficiency are reduced compared to the nominal power. Relatively long startup times and inability to resond to rapid fluctuations in the electric input causes challenges when incorporating an alkaline electrolysis into a power to gas process [18, p. 26].

If the electrolyzer works in an atmospheric pressure, the product hydrogen usually has to be compressed for transportation of grid injection. This causes an energy loss equal to the compressing work. The electrolyzer can be set up to work in an elevated pressure, which results in a decrease in gas quality and electro-chemical efficiency, but the overall efficiency is increased due to the lack of the hydrogen compression [13, p. 1372].

3.4.2 Proton exchange membrane electrolysis

Also known as polymer electrolyte membrane electrolysis and referred to as PEM or PEMEC, this method uses a solid polymer electrolytes, unlike the alkaline electrolysis in which liquid electrolyte is used. Proton (H^+) is the ion that is transported from the anode to the cathode, passing through the polymer membrane. A schematic picture of a PEM electrolysis cell and its working principle is shown in figure 2.

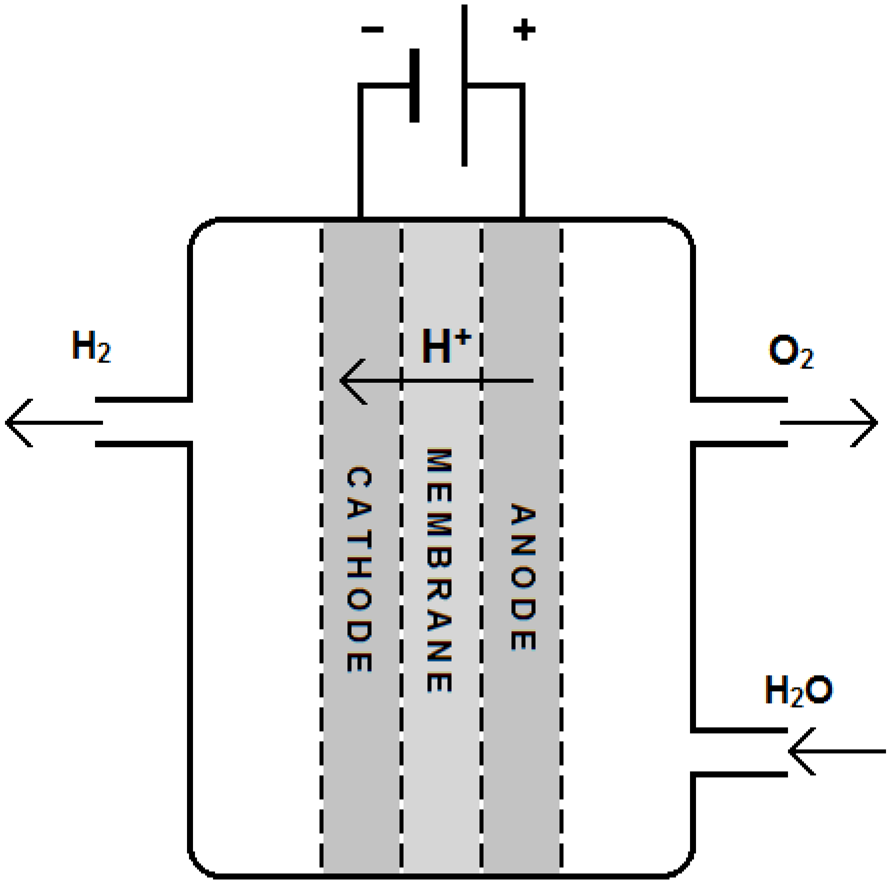

Figure 2: Basic structure and operation of a PEM electrolysis cell.

The electrochemical reactions in cathode and anode are described in equations 3.8 and 3.9.

$$2\,H^+ + 2\,e^- \rightarrow H_2 \qquad (3.8)$$

$$H_2O \rightarrow \tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- \qquad (3.9)$$

The main advantage of PEM over the alkaline electrolysis technology is its ability to follow dynamic electric input, as it can respond to load changes in hundreds of milliseconds. The electro-chemical efficiency is 60 – 70 %, and the PEM cells typically operate at pressures of 30 – 60 or even up to 200 bar, which reduces the losses of energy in hydrogen compression. (lehner 30). The purity of the product gas is also very high, and the practical load range is very wide beginning from 5 % of nominal power [13, p. 1373].

The PEM technology seems very promising for power to gas applications, but some major challenges are present. Currently the PEM cells are difficult to upscale into larger plant sizes and the cost of materials is quite high. Due to the relatively immature stage and the ongoing research and development of the PEM technology, overall improvements are to be expected, including better efficiencies, larger unit sizes and lower costs.

3.4.3 Solid oxide electrolysis

Referred to as SOEC, this technology is the latest and least mature one. Different from the two other technologies, water in this process is in steam form. Oxygen ions carry the charge through a solid oxide membrane which acts as the electrolyte. The basic structure of a solid oxide electrolysis cell is shown in the schematic of figure 3 [18, p. 33].

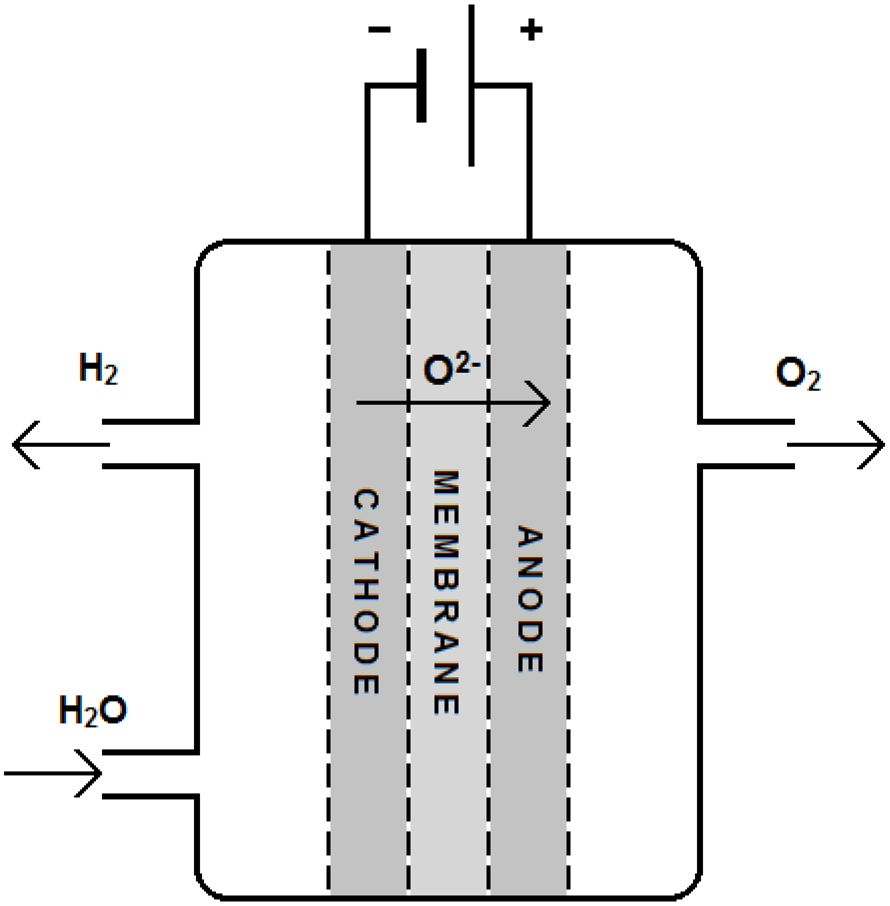

Figure 3: Basic structure and operation of a SOEC.

Reactions in cathode and anode are presented in equations 3.10 and 3.11.

$$H_2O + 2\,e^- \rightarrow H_2 + O^{2-} \qquad (3.10)$$

$$O^{2-} \rightarrow \frac{1}{2}\,O_2 + 2\,e^- \qquad (3.11)$$

Solid oxide electrolysis cells operate at very high temperatures of 700 – 1 000 °C, compared to other electrolysis methods. Typically atmospheric pressures are used. The main advantage of this technology is the high efficiency, which is reported to be over 90 %. The SOEC systems are also capable of revered operation, in which the device will function as a fuel cell. The reversed operation is utilized in the DEMETER project in France. The SOEC device is also capable of reducing CO_2 to CO electrochemically, this function is featured in a Power-to-Liquids demonstration plant in Dresden, Germany. A dynamic operation is possible if temperature control is adequate, otherwise stability issues with fluctuating power sources have been reported [13, p. 1373]. SOEC devices are subject to rapid degradation due to the high operating temperature and lack of durable materials, which is the main issue to be resolved before the technology can be widely commercialized [18, p. 36].

3.5 Methane

Methanation itself is not a mandatory step for a power to gas process as the energy can be stored and distributed in the form of gaseous hydrogen, but the readily available applications for synthetic natural gas make it a very interesting process, in spite of the added technical complexity and loss of efficiency. The overall reaction in which hydrogen and carbon dioxide gases react to form methane is called the Sabatier reaction, and is described in equation 3.12.

$$CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O \quad \Delta H = -165.0 \text{ kJ/mol} \qquad (3.12)$$

In the Sabatier reaction, the carbon dioxide reacts with hydrogen and forms intermediate carbon monoxide in an endothermic reaction described in equation 3.13.

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H = +41.2 \text{ kJ/mol} \qquad (3.13)$$

Subsequently the carbon monoxide reacts exothermically with gaseous hydrogen and produces methane.

$$CO + 3\,H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H = -206.2 \text{ kJ/mol} \qquad (3.14)$$

As it can be seen from equations 3.12 and 3.14, both CO_2 and CO can be used as the carbon source in methanation. In the original and still dominating applications of methanation, carbon was brought into the process from the gasification product of coal [18, p. 43 & 52]. In these processes the carbon monoxide is the substantial feedstock. In sustainable applications such as power to gas, the carbon dioxide is more significant input of the reaction. It can be extracted from flue gases of a combustion plant, gasification of biomass, product gas from a biogas plant or from the atmosphere, the most abundant source of CO_2. The extraction from atmosphere could close the loop for the use of carbon and make the process carbon free, but it would need a substantial amount of energy and significantly decrease the efficiency of the process. If the source of carbon was the flue gases from a fossil fuel burning combustion plant, the methanation would be considered as a reuse of carbon, which would reduce the carbon emissions by max 50 %. However, using a concentrated CO_2 source will improve the efficiency of the methanation process itself. Currently biogas and biomass gasification are the most promising sources of CO_2 [8, p. 444; 13, p. 1386; 19].

Methanation methods available today require relatively steady inputs of feedstock, so due to the intermittent output of hydrogen from electrolysis, an intermediate storage of hydrogen and preferably also carbon dioxide is required. The parameters of design are very diverse in different power to gas concepts, e.g. the fluctuation range and peak output of electric power, intermediate storages of feedstock gases, the source of CO_2 and the quality requirements of the natural gas grid and end applications, which limits the flexibility and scalability of the concepts, and each facility and process is made for very specific standards. Because of the early stage of development, the process of methanation is in experimental phase and current projects are mostly demonstration plants built to gain experience and data for the possible commercial plants in the future [18, p. 52-58].

3.5.1 Catalytic methanation

The Sabatier reaction requires high temperature and elevated pressure compared to atmospheric conditions, and a presence of a catalyst. The most used catalyst in methanation is nickel, while ruthenium, cobalt and iron are actively investigated. The catalytic methods are developed for industrial applications and typically require steady inputs. In power to gas concept this is discordant with the fluctuating nature of the renewable energy sources, and sets requirements for the control of the process. The high temperatures occurring in the exothermal reactions of catalytic methanation make it technically easy to utilize the waste heat in steam and power production and improve the process efficiency. Maximum chemical efficiency of catalytic methanation can be expected to be 78 % [13, p. 1381-1382].

Catalytic methanation reactors can be divided into three main types. Fixed-bed reactors operate adiabatically in wide temperature range of 250 – 500 °C, and the reaction occurs in multiple reactors connected in series, with gas cooling and process heat recovery between the reactors. Due to the aforementioned exothermal nature of the reaction, the temperature rises rapidly in the reactor, hence the process is divided into cascade of reactors and special attention to temperature control is given. The solid catalyst is in a pellet form and forms a static bed, while the inputs of CO/CO_2 and H_2 are gaseous.

Fluidized-bed reactors have more static thermal conditions. The solid catalyst particles are fluidized by the applied gas, which creates a strong turbulent state in the reactor that allows the high temperature transfer rate. The gas flow rate is restricted to a certain range due to the fluidization, hence this type of reactor is not suitable for fluctuating loads.

Bubble column reactor utilizes a liquid medium as a heat carrier. The liquid transfers the exothermic heat efficiently and isothermal conditions similar to a fluidized bed reactor are achieved, with reduced abrasion of the materials. In early projects, mineral oil was used as the heat carrier medium, but modern concepts have introduced ionic fluids which behave better on partial loads and enable more modular design of the reactor [13, p. 1375-1376].

3.5.2 Biological methanation

Biological methanation process involves microorganisms that form methane, and no chemical catalyst is present. For the most advanced projects, a selectively evolved strain of archaea originally developed in the University of Chicago is currently used. Inputs for the process are hydrogen and carbon dioxide, the overall chemical reaction is equivalent to the Sabatier reaction. The reaction takes place in anaerobic conditions in an aqueous solution of the cell culture, maintenance reagents and dissolved gases. The operating temperature is not as high as in the catalytic method, about 60 – 65 °C or less, and the carbon conversion efficiency is very high at up to 98.6 %. The process takes place in mostly atmospheric pressure. The process is also quickly responsive for variations of the inputs in certain range and is tolerable for impurities, but the speed in which methane is formed is slower than the catalytic process.

Figure 4: A biological methanation reactor used in the Foulum project, Denmark [20, p. 16].

The power to gas efficiency of a biological methanation process can reach to 78 % when the released heat is recovered. Without the heat recovery the efficiency reaches 58 %. Due to the relatively low temperature level, there are not many applications for the utilization of the waste heat [20, p. 8 & 10; 13, p. 1381].

Biological methanation process can efficiently be coupled with a biogas plant, in which digestion and anaerobic decomposition of organic material forms methane and carbon dioxide. The product gas from the digestion contains 50 – 70 % methane and 30 – 35 % carbon dioxide.

As the carbon dioxide is a wanted feedstock for the methanation and the archaea are tolerant for common impurities such as H_2S, adjoining these processes works for both upgrading the biogas and methanation of the electrolytic hydrogen. The two processes can optionally be integrated into one single reactor, where both reactions occur simultaneously. In concepts where the biological methanation takes place in a separate reactor, different sources of carbon are possible and the process conditions can be adjusted more suitable for the hydrogen-consuming microorganisms [13, p. 1381].

3.6 Power to liquids and power to fuels

The renewable energy can be stored in liquid form as well as gaseous. Most common end products besides preciously introduced hydrogen and methane are methanol, formic acid and liquid fuels. Different processes and feedstocks are used for different end products, but in general case, electrolytically produced hydrogen is further reacted with a carbon source to form new compounds. Fischer-Tropsch-synthesis and catalythic conversions are the most used processes when producing liquid end products. Because of the wide array of process paths, the concept of power to liquid is not specified in further detail, nonetheless it is important to be conscious of this concept, as it is closely related to power to gas. Out of the facilities presented in section 4, liquid end products were produced in three plants (Minerve, Power-to-Liquids Dresden, George Olah) [18, p. 13].

3.7 Efficiencies

Efficiencies of power to gas processes are dependant to some degree on the pressure of the end product as the pumping of gas to higher pressure results in energy loss. The electrochemical efficiencies between different electrolysis technologies also have variation, and in high-temperature processes the waste heat utilization becomes significant. When adjoined by a methanation process, the source of CO_2 plays a major role in the process efficiency, as discussed in section 3.5.

From reasons mentioned above, numerical values for efficiencies are very sweeping and dependant on the particular application and its adjoining processes. A round-trip efficiency for power to hydrogen to power (electricity) can be considered to be in the range of 34 – 44 %, and power to hydrogen to CHP about 48 – 62 % [18, p. 10]. If conservative values for a generic case are needed, about 40 % for electric and 55 % for CHP are roughly the average values.

In the case of power to methane to power, the added complexity introduces more losses, hence the efficiencies are lower. For power to methane to power (electricity), a range of 30 – 38 % is given, and power to methane to CHP 43 – 54 % [18, p. 10]. For simplified generic values, 35 % for electric and 50 % CHP efficiencies are hereby suggested.

As presented in section 3.4, the other main product of electrolysis besides hydrogen is gaseous oxygen. While not directly having an effect on electro-chemical efficiencies of the concepts, the utilization of oxygen produced in high purities of 99.2 % and above can have a significant economical value, if a market for oxygen is present [21, p. 7 & 18]. However, the optional compression and distribution of oxygen adds complexity and costs for a power to gas –facility.

4 REVIEWED PROJECTS

The projects listed here are actual plants with electric input and hydrogen or methane or other chemical output. The plants can be planned, operational or decommissioned. The status and schedule of each individual facility is listed, along with the partners involved in the project. Projects in which single components, business models or simulations are developed are excluded. Gas production via gasification or biogas digestion is also excluded, with the exception of when the process is coupled with electrolytic hydrogen production.

4.1 Asia

4.1.1 China: Hebei

McPhy Energy has signed a contract in 2015 to deliver a hydrogen system to recover surplus energy of a 200 MW wind farm in the province of Hebei, China. The German State of Brandenburg and the Chinese province of Hebei have a joint development agreement for renewable energies, and within its framework Hebei plans to build a hybrid power plant similar to the one in Prenzlau, Germany. McPhy will provide two hydrogen production lines with total input power of 4 MW. The delivery also includes a transportable solid state storage unit that is used in conjunction with traditional tanks. The delivery is scheduled for July 2016 and the equipment is to be commissioned in the beginning of 2017 [24; 25].

Status: planned, commission to begin in 2017

Project partners: Jiantou Yanshan Wind Energy, McPhy Energy SA, ENCON.Europe GmbH

4.1.2 Japan: Tohoku

The concepts of power to gas and carbon recycling were originally introduced in Japan, and the first demonstration plants were commissioned in Tohoku. The first power to gas prototype system was built in 1995, on the rooftop of the Institute for Materials Research of Tohoku University. The system received its electric power from a photovoltaic unit located in a desert, and it had 32 electrolytic cells which produced hydrogen from seawater. Two reactors converted carbon dioxide and the hydrogen to methane. The methane was combusted and the released CO_2 was captured and sent back to the methanation process as a feedstock. This prototype proved successfully that with access to solar power, hydrogen and methane can be produced from seawater and CO_2 can be recycled in this process. The electrolysis technique is high-temperature alkali electrolysis of desalinated seawater, which was chosen over the direct electrolysis of seawater due to technical problems and energy consumption.

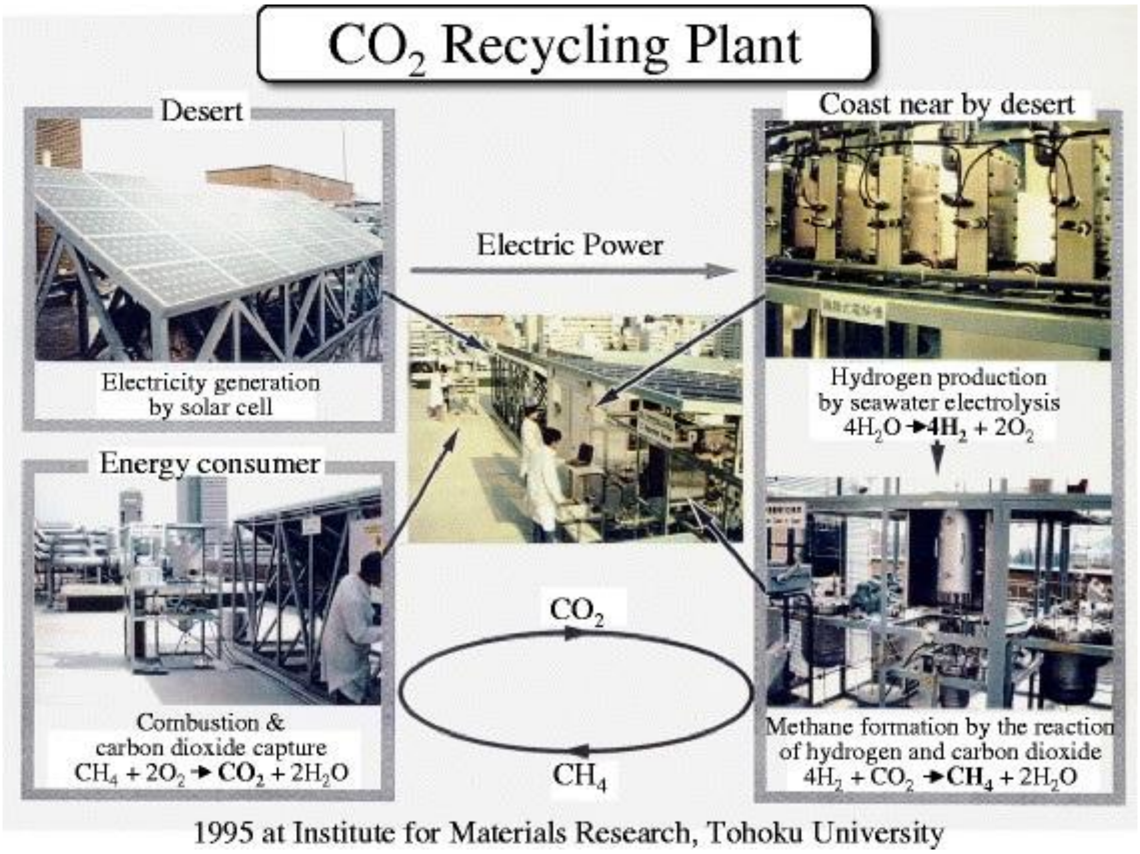

Figure 20: The prototype CO2 recycling plant in Tohoku University [100].

A pilot plant of larger scale was built at the Tohoku Institute of Technology in 2003. The capacity for hydrogen production is 4 Nm³/h and for methane production 1 Nm³/h. The hydrogen is produced electrolytically from seawater in this plant also [100; 101].

Status: unknown, plants built in 1995 and 2003

Project partners: Tohoku University, Tohoku Institute of Technology

4.2 Europe, Germany

4.2.1 Germany: CUTE and HyFLEET:CUTE

The city of Hamburg participated in the CUTE and its successor HyFLEET:CUTE projects with up to nine fuel cell buses. The hydrogen was produced via on-site electrolysis using certified green electric power. The hydrogen was produced with an electrolyzer by Norsk Hydro Electrolysers, with the capacity of 60 Nm³/hand and an electrical input of 390 kW. The demonstration project was successful and the technology was functional enough to extend the buses operation until 2011 [41; 42].

Status: completed, schedule 2003 – 2011

Project partners: Hamburger Hochbahn AG, Vattenfall GmbH, Norsk Hydro ASA, BP plc (British Petroleum), European Commission

4.2.2 Germany: Reussenköge

GP JOULE has put into operation the first phase of its project that is dubbed “power gap filler” by the company. The power gap filling, an alternative designation for grid balancing, is achieved by connecting altogether 40 PEM electrolyzers (four in this first phase) the grid, with the output of 5 kW each and 200 kW total. The hydrogen is stored and converted back to electricity with biogas in a CHP plant. The residual heat produced in the electrolysis is fed into local heating grid. The hydrogen stored can also be used in industry or as a fuel for vehicles, but it is uncertain if there are any actual facilities, e.g. fueling stations being built.

Located in the German state of Schleswig-Holstein where more than a quarter of Germanys wind energy capacity is built, the location is very propitious for making use of the excess energy of off-peak wind energy production. The power gap filler in Reussenköge is a pilot project, and GP JOULE has plans to build a combined heat and power plant that integrates PEM electrolyzers and a biogas plant. The electrolysis stack will have a power input of one megawatt. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU) provides research funding on 2.1 million euros for this project [43].

Status: first phase (4 electrolyzers) operational, second phase (36 electrolyzers) in commission, new plant is planned

Project partners: GP JOULE GmbH, German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU)

4.2.3 Germany: Schnackenburgallee

Shell opened a hydrogen fueling station on Schnackenburgallee in Hamburg, the first of its kind to Shell where the hydrogen is produced on site. PEM electrolyzers are used for hydrogen production, the electric power is 50 % certified green energy and the rest 50 % are from operating reserve of the electric grid [44].

Status: operational since 2015

Project partners: Shell, National Organization for Hydrogen and Fuel Cell Technology (NOW), Clean Energy Partnership (CEP)

4.2.4 Germany: HafenCity

A hydrogen fueling station for buses and cars was opened by Vattenfall in the quarter of HafenCity, Hamburg. About half of the hydrogen the station uses is produced on site by two electrolyzers using renewable energy [45; 46].

Figure 7: The HafenCity hydrogen fueling station [45].

Status: operational since 2012

Project partners: Vattenfall GmbH, Clean Energy Partnership (CEP), Hamburger Hochbahn AG, Shell, German Transport Ministry

4.2.5 Germany: Prenzlau

Located in Prenzlau, this hybrid power plant integrates a biogas unit, three wind turbines of 2 MW each, an electrolysis unit and two CHP plants. In addition to co-firing the power plants, the hydrogen produced in the electrolysis can also be used as a fuel for cars. After McPhy Energy acquired the division of Enertag which built the 0.5 MW alkaline electrolyzer, it further optimized the technology and integrated into electrical and natural gas networks. Since November 2014 the hydrogen has been injected into the natural gas network [47; 48].

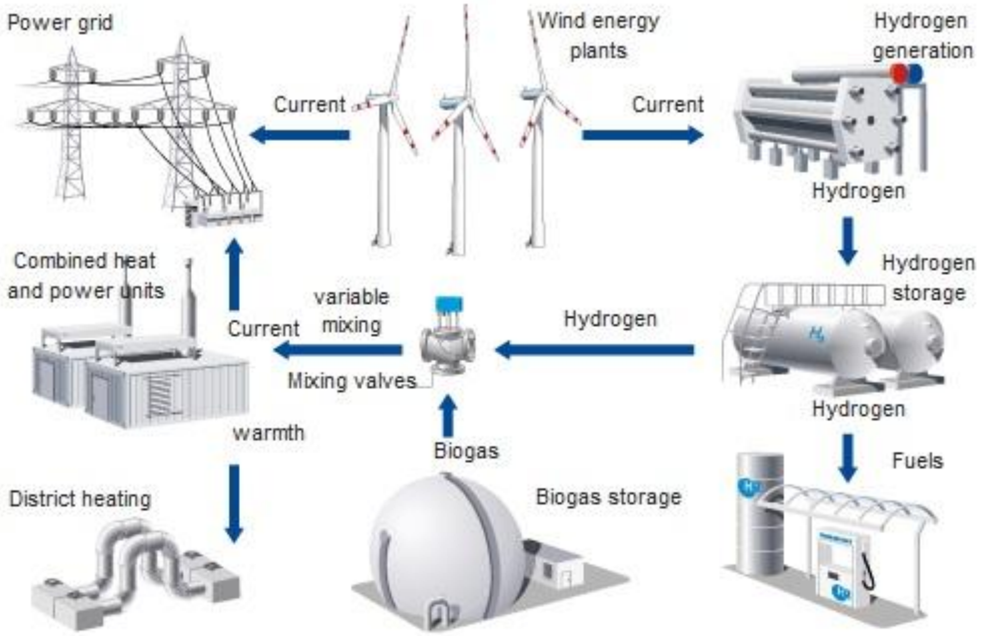

Figure 8: The Prenzlau hybrid power plant. Hydrogen injection to gas grid was added later [49].

Status: operational since 2011

Project partners: Vattenfall GmbH, Enertrag AG, McPhy Energy S.A., Total S.A., Siemens AG, German Ministry of Transport

4.2.6 Germany: Werlte

The plant produces synthetic methane called Audi e-gas. The plant uses three electrolyzers with total power input of 6.3 MW to produce hydrogen from intermittent wind power. The hydrogen is reacted with carbon dioxide in a chemical-catalytic process under high pressure and temperature. The CO_2 is extracted from a nearby biogas plant and the end product is synthetic methane which is injected to the natural gas transmission network. With its annual e-gas production of about 1 000 metric tons, the plant can supply a fleet of 1 500 Audi A3 gas vehicles with the kilometer performance of 15 000 km annually.

Figure 9: The Audi e-gas plant [51].

The conversion efficiency from electricity to gas is around 54 %, but the total efficiency of the plant is higher since the waste heat is recycled in the processes and utilized also in the adjoining biogas plant. The plant recycles around 2 800 tons of CO_2 annually [50; 51; 52; 53].

Status: operational since 2013

Project partners: Audi AG, ETOGAS GmbH

4.2.7 Germany: Ibbenbüren

The plant in Ibbenbüren links together local renewable power production, natural gas grid and district heating. The plant is owned and operated by RWE Deutschland AG and the main component of the plant, a rapid response PEM electrolyzer system with rated output power of 150 kW, is built by ITM Power. The electrolyzer system incorporates a heat recovery system, which has allowed the plant to gain a measured overall energy efficiency of 86 %. In times of low renewable energy production and high power demand, a co-generation plant within the district heating network of RWE uses gas from the natural gas grid to produce heat and power [54].

Status: operational since 2015

Project partners: RWE Power AG, ITM Power plc.

4.2.8 Germany: H2Herten

Several companies and institutions who are supporters of renewable energy are settled on the old Ewald colliery in Herten, and are forming the Herten Hydrogen Center of Excellence. There are two hydrogen production facilities on the site which produce hydrogen electrolytically from wind power. The electrolysis plants are part of H2Herten user centre's decentralized power supply, which also serves as a platform for research and demonstration. A hydrogen filling station which is located on the area is partly fed by the hydrogen produced on site [55; 56].

Status: operational

Project partners: numerous members of Wasserstoff Kompetenz Zentrum, Government of North Rhine-Westphalia, European Union

4.2.9 Germany: CO2RRECT

The CO2RRECT project was funded by the Federal Ministry of Education and Research. The aim of the project was to develop a process to convert CO_2 extracted from flue gases of power stations into synthesis gas, a raw material for industry. CO_2 is reacted with H_2 produced by electrolysis with renewable power. In Niederaussem, 7.2 tonnes of CO_2 is extracted daily from the flue gas of a lignite power plant. Siemens built a PEM electrolyzer for this project with nominal capacity of 100 kW, and peak capacity up to 300 kW.

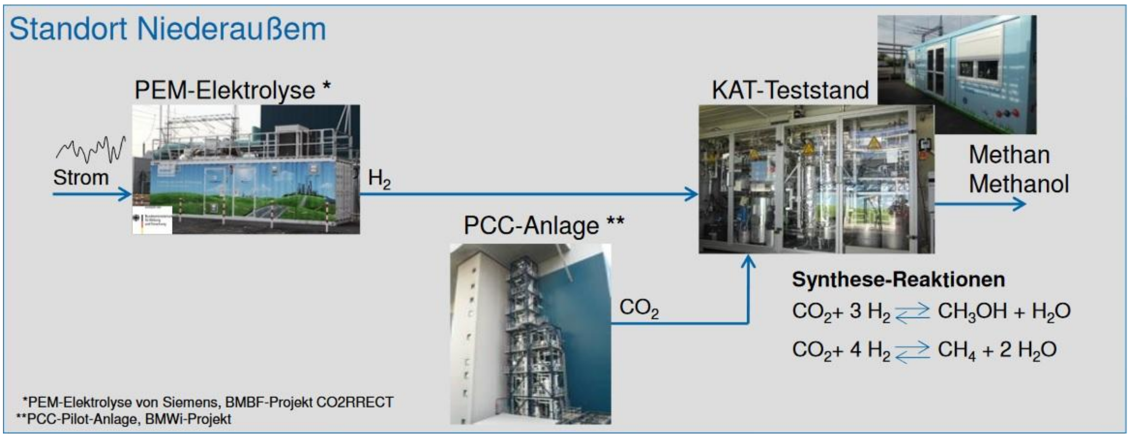

Figure 10: The main scheme and main reactions of the Niederaussem project [59].

In the project, processes for both methane and methanol were used. Bayer and project partners continued the utilization of extracted CO_2 as a raw material in their next demonstration plant in Leverkusen. In the Leverkusen plant, CO_2 and hydrogen are used to produce polymers and formic acid [57; 58; 59; 60].

Status: completed, schedule 2009 – 2014

Project partners: RWE AG, Siemens AG, Bayer AG, Linde AG, German Ministry of Education and Research

4.2.10 Germany: BioPower2Gas

This facility combines a biogas plant with a PEM electrolyzer, the end product being biomethane that is injected into the natural gas grid. The electrolyzer has an input capacity of 400 kW and its maximum hydrogen production is 400 Nm^3/h. The electric grid power used is surplus power from renewable sources. The use of PEM electrolyzer and biological methanation enables great variation in input power and the use of the plant for grid balancing, which is studied in this demonstration plant.

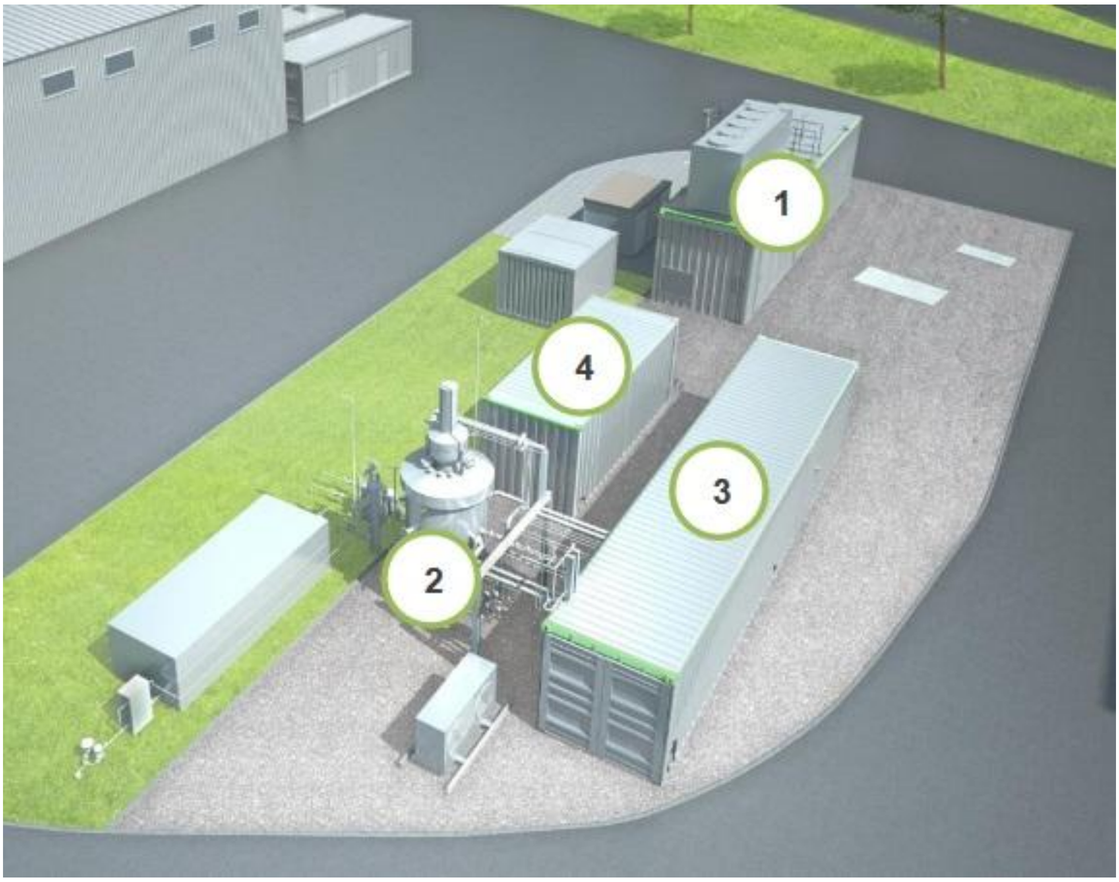

Figure 11: Layout of the BioPower2Gas system. 1) PEM electrolyzer, 2) biological methanation pressure vessel, 3) auxiliary devices, 4) control equipment [61].

The flexible power storage system consists of three facilities. The biomethane plant located in Allendorf produces biomethane when surplus electricity is available, and in Philippsthal a gas-powered CHP plant which is supplied from the gas network produces electric power and district heat with flexible demand. An additional biogas plant in Jühnde produces biogas in a conventional way and stores it, and produces electric power and heat whenever periods of increased demand occur [51; 61; 62; 63].

Status: operational, schedule 2013 – 2016

Project partners: MicrobEnergy GmbH (Viessmann Group), CUBE Engineering GmbH, EAM EnergiePlus GmbH, IdE Institut dezentrale Energietechnologien gGmbH, Audi AG

4.2.11 Germany: Frankfurt am Main

This plant will participate in the market for secondary control power by providing negative balancing power. When too much electric power is on the grid and the grid operator requests, the plant increases the input for its PEM electrolyzer and converts the excess power into hydrogen. The hydrogen is then injected into the Frankfurt am Main natural gas distribution network through a gas mixing station, which ensures that the hydrogen content of the network does not exceed two percent by volume. The plant first injected hydrogen into the gas network in 2013 and the plant's operational and research phase runs to the end of 2016.

The plant's relevant load range is from 50 to around 325 kW, and the overall efficiency from electrical input to gas injection is recorded to be up to 77 percent. One of the factors contributing to the high efficiency is the direct injection of gas to the gas network, which eliminates the need for a compressor. The participants of this project are planning a follow up project, which would include reacting hydrogen with CO_2 to produce methane and feeding it into the gas network [64; 65].

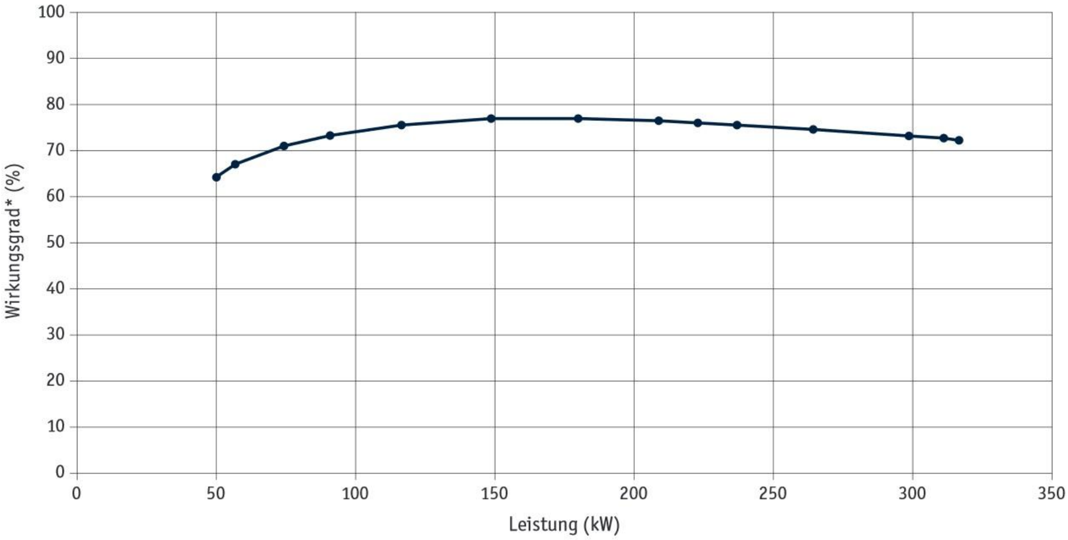

Figure 12: Recorded efficiency of the Thüga group's power to gas –plant [65].

Status: operational, schedule 2014 – 2016

Project partners: Badenova AG & Co. KG, Erdgas Mittelsachsen GmbH, Energieversorgung Mittelrhein GmbH, Erdgas Schwaben GmbH, ESWE Versorgungs AG, Gasversorgung Westerwald GmbH, Mainova Aktiengesellschaft, Stadtwerke Ansbach GmbH, Stadtwerke Bad Hersfeld GmbH, Thüga Energienetze GmbH, WEMAG AG, e-rp

GmbH, Thüga AG, ITM Power plc., Hessian Ministry for the Environment, Agriculture and Consumer Protection, The Fraunhofer Institute, the European Union

4.2.12 Germany: Energiepark Mainz

Energiepark Mainz is a project currently being commissioned in Mainz-Hechtsheim. In the facility three DC stations with input power of 2 MW each will generate direct current needed for the electrolysis process. The electric system is connected to the medium voltage (20 kV) grid and an adjacent wind farm of 8 MW. The hydrogen is produced by three PEM electrolyzers built by Siemens, with continuous power of 1.3 MW and peak power of 2.0 MW each. The output pressure of the hydrogen gas is 35 bar and no mechanical compression is needed. After purification and drying the hydrogen is either stored on site in two containers of 82 m^3 each, injected into the natural gas grid or delivered to the trailer filling station, from where it can be transported to various destinations and uses [66].

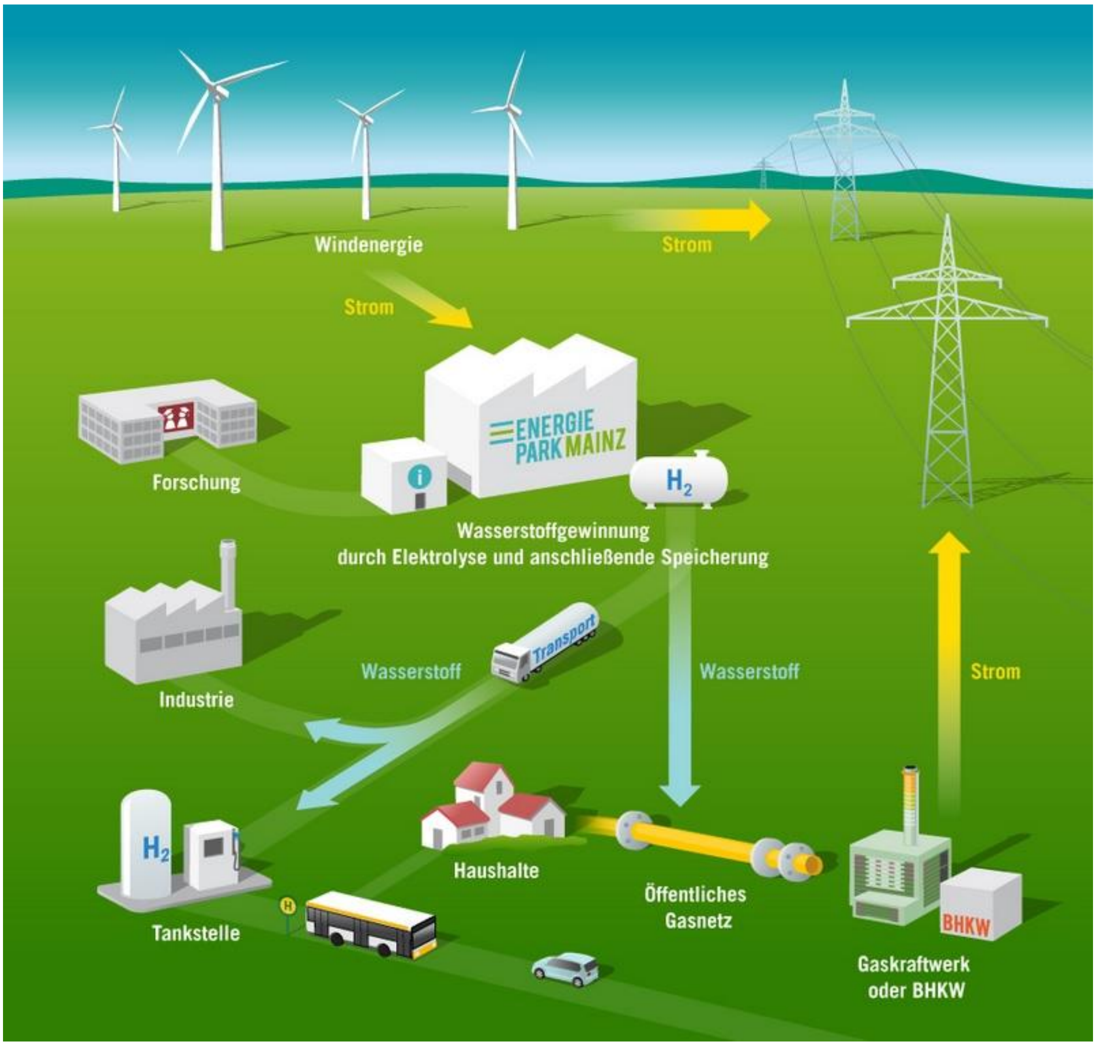

Figure 13: The concept of the Energiepark Mainz [66].

Status: in commission, project started in 2012

Project partners: Siemens AG, Linde AG, RheinMain University of Applied Sciences, Stadtwerke Mainz, German Federal Ministry for Economic Affairs and Energy

4.2.13 Germany: Stuttgart

This research plant converts renewable electricity into hydrogen and methane. The hydrogen is produced in an alkaline pressure electrolyzer with the input power of 250 kW. The methane output is up to 300 Nm³ per day. The plant works dynamically and intermittently, which is needed when electric power from renewable sources is used. The project partners have built a prior plant of smaller scale, which had an electric power of 30 kW and it had more static operation which is typical for earlier types of processes [67].

Status: operational since 2012

Project partners: Center for Solar Energy and Hydrogen Research (ZSW), Fraunhofer IWES, SolarFuel GmbH (now ETOGAS GmbH), German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

4.2.14 Germany: H2Move

H2Move is a hydrogen filling station in Freiburg, which is operated by Fraunhofer Institute for Solar Energy Systems. The hydrogen is produced on site via PEM electrolyzer with an output of 0.5 kg/h. The station has a photovoltaic power production of 16 kW peak which is used for the electrolysis. If power production exceeds the input need of the electrolyzer, the surplus power is fed to the local power grid of the Fraunhofer institute. The oxygen is released into the atmosphere and the hydrogen is dried, compressed and stored on site in 450 and 950 bars. The hydrogen is then dispensed in the fueling station to hydrogen powered vehicles or to separate tanks to be transported and used in a variety of purposes. This station is connected to the CEP-network, and fueling here requires a CEP (Clean Energy Partnership) card [68; 69].

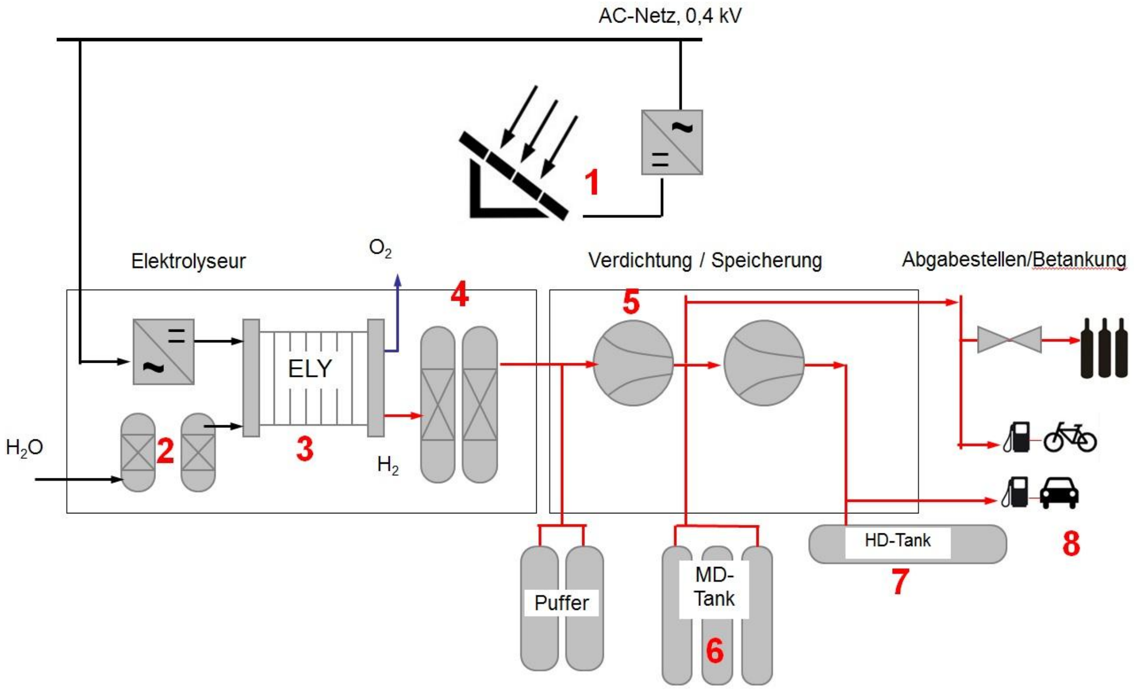

Figure 14: Power and hydrogen production and dispensation in the H2Move station [68].

Status: operational since 2013

Project partners: Fraunhofer Institute for Solar Energy Systems (ISE), Clean Energy Partnership (CEP), Badenova AG & Co. KG, State of Baden-Wuerttemberg, City of Freiburg

4.2.15 Germany: Schwandorf

This research project couples waste water treatment plant with electrolytic production of hydrogen. An electrolyzer produces hydrogen with the capacity of 30 Nm^3/h, and this hydrogen is reacted in a biological process with product gas of the adjoining water treatment plant. Microorganisms in the digester consume the carbon dioxide of the water treatment plant's product gas and hydrogen from the electrolysis, and produce methane [70].

Status: operational since 2014

Project partners: MicrobEnergy GmbH, University of Regensburg, Zweckerband wastewater treatment plant, Bavarian Ministry of Economic Affairs, Infrastructure, Transport and Technology

4.2.16 Germany: MicroPyros

The MicroPyros project combines biogas and renewable energy and produces synthetic natural gas via biological methanation. In Straubing a proof-of-concept plant is built, where biogas from a local waste water treatment facility is reacted biologically with hydrogen produced via electrolysis [71; 72].

Figure 15: The water treatment facility in Straubing [71].

Status: active, schedule 2014 – 2017

Project partners: MicroPyros GmbH, BOREAS, Holzner Druckbehälter, Fraunhofer Institute for Enviromental, Safety and Energy Technology (Fraunhofer UMSICHT)

4.2.17 Germany: Hassfurt

A consortium is planning a power to gas plant in Hassfurt. The plant will use surplus renewable energy from the electric grid. PEM electrolyzers by Siemens, with the total power input of 2.1 MW will be used to produce hydrogen, which will be stored on site in the pressure of 30 bars in total volume of 110 m³. The first step of the project is to use the hydrogen in a CHP plant. In the second phase, the hydrogen is injected into the natural gas distribution network with gradually increasing concentrations of up to 5 % [73].

Status: planned

Project partners: Stadtwerk Hassfurt GmbH, GUT Hassberge mbH, Siemens AG, University of Applied Sciences Würzburg-Schweinfurt (FHWS), Linde AG, DBI Gas- und Umwelttechnik GmbH, TÜV Süd, Greenpeace Energy, TTZ-E-Mobilität

4.2.18 Germany: HYPOS

The HYPOS project (Hydrogen Power Storage & Solutions East Germany) aims to utilize the surplus renewable electricity in the energy system. Project partners are planning to build a demo center for large scale electrolyzers. The hydrogen will be used as a raw material for chemical industry, as well as an energy source for electromobility. A storage system for the hydrogen will be decided after site analyses, connections to pipelines and storage in caverns are studied. The demo center will allow the most modern electrolysis systems to be validated, and new operating strategies will be developed to respond to the changes in the overall energy production [74; 75].

Status: planned

Project partners: Fraunhofer Institute for Mechanics of Materials, Verbundnetz Gas AG, Forschungszentrum Jülich (Jülich Research Centre)

4.2.19 Germany: Power-to-Liquids

Located in Dresden, this plant operated by Sunfire produces liquid fuels via a three step process. In the first step, hydrogen is produced using solid oxide electrolysis cells (SOEC) and renewable electrical energy. In the process, water is in steam form rather than liquid. The second step is the reverse water-gas shift reaction, in which carbon dioxide is reacted with the hydrogen and is reduced to carbon monoxide (CO). The final step is Fischer-Tropsch process, where the carbon monoxide and the hydrogen are converted to fuels such as petrol, diesel and kerosene, or base products for chemical industry. The electrolysis system is capable of reversing the process and functioning as a fuel cell, converting the hydrogen reserves or other fuels to electricity and heat during periods of high electricity prices.

Figure 16: Power to liquid plant in Dresden [77].

The plant's capacity for CO_2 recycling is 3.2 tonnes per day, and it can produce up to 160 liters of fuel per day. The process has an overall efficiency of 70 %, such a high number is due to the recycling of the released process heat. The commercialization of the plant is scheduled for 2016 [76; 77].

Status: operational

Project partners: sunfire GmbH, Audi AG, Federal Ministry of Education and Research

4.2.20 Germany: Cottbus

This research & development project called "Hydrogen production from renewable energy sources" is jointly executed by Brandenburg University of Technology and Enertag AG. In this project, an advanced high pressure alkaline electrolyzer prototype was commissioned, tested and optimized at the Brandenburg University of Technology's Test Station for Renewable Energies located in Cottbus. The focus is also in the control systems of the electrolyzer which would connect the electrolyzer into a hybrid power plant. The electrolyzer can operate at a pressure of up to 60 bar with the capacity of 30 Nm³/h. The hydrogen is dried, purified and stored on site. The facility has photovoltaic system and a 2.7 kW wind turbine for renewable power production, and a fuel cell system for converting stored hydrogen back to electricity. The facility has also a small PEM electrolyzer with hydrogen production capacity of 1 Ndm³/min and a metal hydride storage of 760 Ndm³ for research [78; 79].

Status: unknown, schedule 2010 – 2013

Project partners: Brandenburg University of Technology Cottbus, Enertag AG

4.2.21 Germany: WindGas Falkenhagen

This pilot plant is commissioned by E.ON in Falkenhagen. The location was chosen due to the abundance of wind power and the existence of power and gas infrastructure. The plant's alkaline electrolyzer is made by Hydrogenics, and it has an electric input of 2 MW and the hydrogen output of 360 Nm³/h. Most of the hydrogen is injected into the natural gas grid, some of the output is delivered to the project partner, Swissgas, and some is made available to the residential customers.

Figure 17: The WindGas plant in Falkenhagen [81].

The operation of the plant has been a success, and it has led to a subsequent project, WindGas Hamburg, which features a PEM electrolyzer of an industrial scale [80; 81].

Status: operational since 2013

Project partners: E.ON SE, Swissgas AG, Hydrogenics

4.2.22 Germany: WindGas Hamburg

Based on the good experiences from the previous project in Falkenhagen, a new power to gas facility converting wind power in the form of hydrogen gas was built in Reitbrook, Hamburg. The prototype PEM elecrolyzer was built with components of different manufacturers, and Uniper Energy Storage (subsidiary of E.ON) is the main operator. The input power is around 1.5 MW and the product hydrogen is injected into the gas grid. As the most commercial PEM electrolyzers have an input power around 100 kW, this project aims to develop a plant-scale electrolyzer with significantly increased efficiency compared to traditional alkaline electrolyzers [82; 83].

Status: operational, schedule 2012 – 2016

Project partners: Uniper Energy Storage GmbH, E.ON SE, SolviCore GmbH & Co. KG, Hydrogenics, Greenerity GmbH, German Aerospace Center, Fraunhofer Institute for Solar Energy, National Innovation Programme for Hydrogen and Fuel Cell Technology, German Federal Ministry of Transport and Digital Infrastructure

4.2.23 Germany: H2BER

Located at the Berlin Brandenburg Willy Brandt Airport, this plant uses electric power from a nearby wind farm and on site photovoltaics to produce hydrogen via electrolysis. The alkaline electrolyzer has an input capacity of 500 kW and it can produce over 200 kg of hydrogen per day, which equals to refueling around 50 fuel cell vehicles. The electrolyzer operates at 45 bar. For the hydrogen there are tanks of 45 and 900 bar for gaseous storage and a solid-state storage system with a capacity of 100 kg. Two hydrogen fueling pumps operate at the site, which deliver the produced hydrogen for hydrogen powered cars and buses.

Figure 18: Scheme of the H2BER facility [86].

An on-site CHP plant produces heat and electricity for the facility from the green hydrogen, and it can also be operated on natural gas. Total output of the plant is 1.000 kW. The facility is connected to both electric and natural gas grids, as the surplus production of electricity and hydrogen are fed into the electric and natural gas grids, respectively [84; 85; 86].

Status: operational, implemented in 2014

Project partners: McPhy Energy SA, Total Deutschland GmbH, Linde AG, Enertrag AG, 2G Energy AG, German State

4.2.24 Germany: RH2-WKA

This power to gas facility is located within a powerful 140 MW wind farm in Grapzow. The excess power from 28 wind turbines of the wind farm is converted to hydrogen in three electrolyzers with the total power input of 1 MW. The capacity hydrogen production is up to 210 Nm³/h. The on-site storage system has the capacity of 300 kg of hydrogen. A CHP plant with total electrical output of 250 kW and thermal output of 400 kW uses the stored hydrogen, or it can be injected into the local natural gas grid, depending on operational needs.

Following the completion of this project, a following scheme is planned in the nearby region. Named RH2-PTG (Pripsleben/Tützpatz/Gültz), this planned project will utilize the same 380 kV transformer station that the RH2-WKA project uses [87; 88; 89; 90].

Status: completed, schedule 2009 – 2015

Project partners: RH2-Werder/Kessin/Altentreptow (RH2-WKA), NOW GmbH (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie), Haas Engineering, Architekturbüro Karsten Klünder, Hydrogenics, Senergie GmbH, Andreas Hofer Hochdrucktechnik GmbH, Germany Federal Government

4.2.25 Germany: Stralsund

University of Applied Sciences Stralsund built this Multi-component Laboratory as a demonstration and education project with its partners. In this facility, hydrogen is produced in an alkaline pressurized electrolyzer with the input power of 20 kW and the production capacity of 4 Nm^3/h. The operating pressure of the electrolyzer and the storage system is up to 25 bar and the storage capacity on site is 200 Nm^3. The electric power for the electrolysis is generated via a 100 kW wind turbine and a photovoltaic system of 9.6 kW peak power. The hydrogen is converted back to electricity via a PEM fuel cell of 370 W, and to heat via catalytic burners of 21 kW_{th}. For educational purposes a co-generation plant is also installed, with an output of 30 kW_{el} and 70 kW_{th}. It is normally fed by natural gas, but the use of mixture of hydrogen and natural gas is experimented. The system has also a diesel generator for isolated network use. The hydrogen can also be filled in containers and delivered elsewhere.

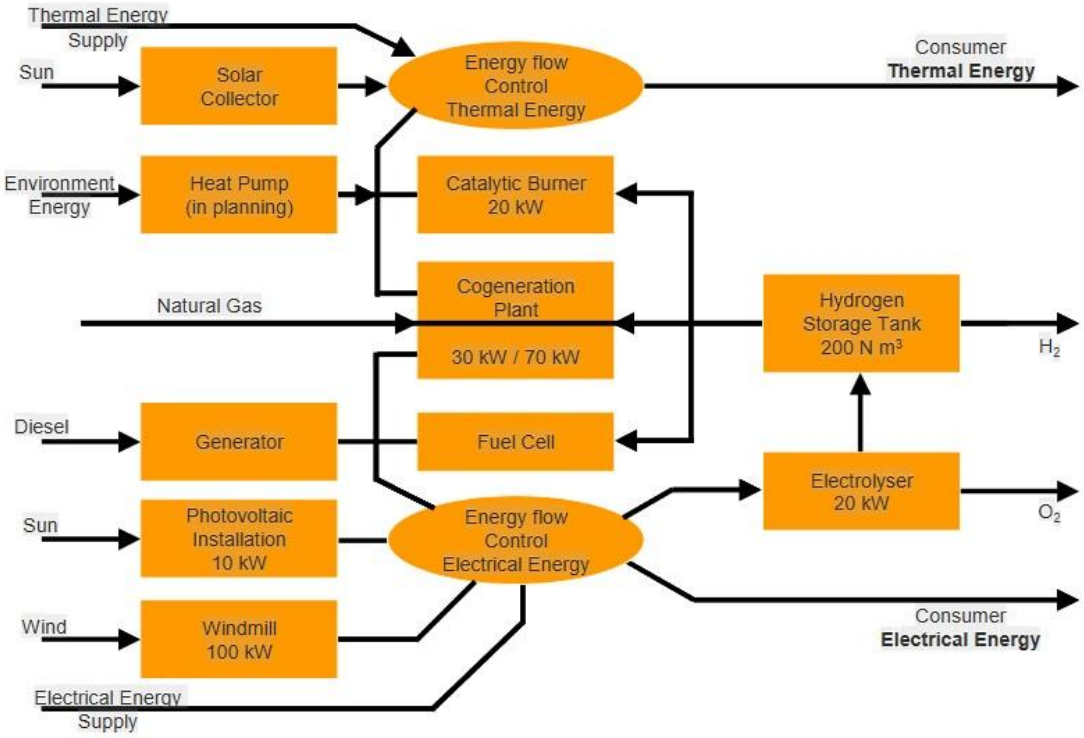

Figure 18: The main components and the energy conversion processes in the Stralsund facility [91].

All components are grid connected, which allows each piece of equipment to be used for separate experiments. It is proven that the electrolyzer can be operated successfully with the fluctuating input from the wind turbine, but for true island operation a different design and smoothing of the input is needed [91].

Status: operational

Project partners: University of Applied Sciences Stralsund, ELWATEC GmbH (Hydrogen Systems GmbH), Spartek Ltd, Ventis Energy AG, ELTA GmbH, ESN EnergieSystemeNord GmbH, TAB GmbH, GePro mbH

4.3. Europe, rest

4.3.1 Denmark: Foulum

Power to gas –technology was tested pre-commercially in the Foulum project, in which a biological methanation was demonstrated. A methanogenic archaea, which was adapted for industrial use in the University of Chicago, was inoculated in a 10.000 liter bioreactor and it produced pipeline-graded methane. The project used raw biogas from an on-site anaerobic digester as the source of CO_2, and the hydrogen was supplied from gas containers. While not directly converting power to gas, this project provided information on efficiency, productivity, robustness and responsiveness of the technology needed for Electrochaea's following BioCat Project, in which a MW-scale commercial technology is used [26; 27].

Status: completed, operational 01-11/2013

Project partners: Electrochaea GmbH, E.ON SE, Energie 360º AG, ewz - Utility Company of the City of Zurich, NEAS Energy A/S, Aarhus University

4.3.2 Denmark: BioCat Project

BioCat Project is located at a wastewater treatment plant in Avedøre. The facility uses alkaline electrolyzer and a biological methanation process. Product methane is injected in a local gas grid. Product heat and oxygen are recycled in the associated wastewater treatment processes. Recycled heat is also in the heating of on-site buildings. Carbon dioxide for the methanation comes from two sources: a raw biogas from a biogas production process, and a pure CO_2 from an on-site biogas upgrading system. The adjoining wastewater treatment plant will provide the biogas.

Electrical input is max. 1 MW at the electrolyzer. The facility provides also frequency regulation to Danish power grid by adjusting the power intake according to the momentary frequency [28].

Status: under construction

Project partners: Electrochaea GmbH, Hydrogenics Europe N.V., Audi AG, NEAS Energy A/S, HMN Gashandel A/S, Biofos A/S, Insero Business Services A/S

4.3.3 Denmark: Vestenkov

In the Vestenkov project a hydrogen community was set up to demonstrate full scale system of hydrogen production, delivery and consumption.

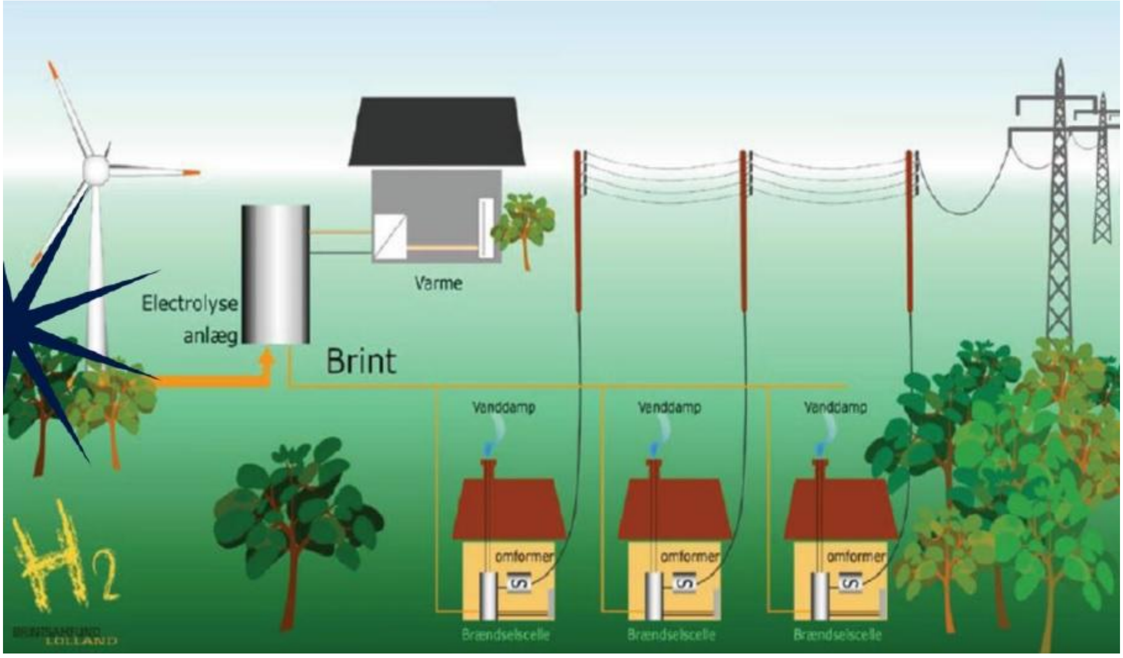

Figure 5: Scheme of the Vestenkov hydrogen system [29, p. 5].

The Vestenkov project consisted of three phases, in which Danish micro combined heat and power units were developed (phase 1, 2007), five prototypes were installed in consumers' houses (phase 2, 2008-2010) and finally 32 units were installed (phase 3, 2010-2014). The units installed in households are hydrogen fuel cells of nominal electric power of 1.5 kW_{el} and thermal power of 1.5 kW_{th}. The combined efficiency is 94 % (47 % for both power and thermal efficiency).

Electrical input of the electrolyzer is max. 104 kW. Continuous hydrogen production is 16 Nm^3/h and continuous oxygen production is 8 Nm^3/h. The volume of H_2 storage is 25 Nm^3 with maximum pressure of 6 bar [29].

Status: completed, schedule 2007 – 2014

Project partners: COWI A/S, Dantherm Power A/S, Danish Gas Technology Centre, DONG Energy A/S, IRD fuel cell A/S, SEAS-NVE, SE, Haldor Topsoe A/S, Danish Parliament, Lolland Municipality

4.3.4 Denmark: MeGa-stoRE

The MeGa-stoRE provided successful proof-of-concept of the power to gas technology by combining a biogas plant with electrolytic production of hydrogen, and using new cleaning processes of the gas. Product gas from the biogas plant (CO_2 and CH_4) is reacted with hydrogen in the Sabatier reaction to produce high quality methane. Main interest was the upgrading of biogas, and the hydrogen production (i.e. power to gas) was the tool to achieve it [30].

Status: completed, schedule 2013 – 2015

Project partners: GreenHydrogen.dk ApS, Elplatek A/S, Lemvig Biogasanlaeg A.m.b.A, DTU (Technical University of Denmark), Aarhus University – Herning

4.3.5 France: GRHYD

The GRHYD project aims to produce hydrogen from surplus renewable electricity. The produced hydrogen is injected into the natural gas network of a new residential neighborhood in Capelle-la-Grande to heat about 200 houses. The hydrogen content of the gas in the network will be varying to up to 20 % by volume. Another application for the produced hydrogen is to produce new *Hythane®* fuel, a gas mixture of hydrogen and natural gas. A natural gas fueling station for vehicles will be adapted to handle this fuel, and around 50 buses will be operated using *Hythane®* [31; 32].

Status: active, schedule 2013 – 2020

Project partners: ENGIE S.A., Gaz Réseau Distribution France S.A., NVERT, AREVA Hydrogène et Stockage de lénergie, CEA (The Alternative Energies and Atomic Energy Agency), McPhy Energy SA, INERIS (National competence centre for Industrial Safety and Environmental Protection), CETIAT (Technical Center for Aerodynamic and Thermal Industries), CeTH2, Dunkerque Urban Community

4.3.6 France: MYRTE

The objective of this project is to develop a system to manage and stabilize relatively small and isolated power network of the island of Corsica. Electric power from a photovoltaic array (560 kW_e) is either fed directly into the power grid or used to produce hydrogen, which is later converted to electric power again via fuel cells. Different operating strategies are implemented in the system control. Several aspects are reviewed, such as the sufficiency of the capacity of the system, the handling of the fluctuations of the photovoltaic output, ageing of materials and testing the ORIENTE simulation software developed by the University of Corsica. The power output from the stored hydrogen is 150 kW [33; 34].

Status: operational since 2013

Project partners: University of Corsica, Areva SE, CEA (The Alternative Energies and Atomic Energy Agency)

4.3.7 France: Minerve

In the concept if this project, a high temperature steam and CO_2 electrolysis is coupled with a CO methanation reactor. The reaction that occurs in the co-electrolyzer in addition to the electrolysis is known as water-gas shift reaction, in which carbon monoxide and water vapor form carbon dioxide and hydrogen. The reaction is described in equation 4.1.

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (4.1)$$

The co-electrolyzer has higher efficiency than traditional electrolyzer (~90 %). The heat from the methanation reactor is recovered and used in the production of the steam. The carbon dioxide is extracted from various industrial sources, and the electric power comes from CO_2-free sources, renewable or nuclear. The end product is methane or further processed liquid fuels [35; 36].

Status: unknown, schedule 2014 – 2015

Project partners: ENGIE S.A., KIC InnoEnergy, CEA (The Alternative Energies and Atomic Energy Agency), Karlsruhe Institute of Technology, AGH University of Science and Technology, Solvay S.A.

4.3.8 France: DEMETER

Technical and economical aspects of energy stocking and destocking are studied and evaluated in the Demeter project. In the concept water vapor and CO_2 are electrolyzed in a solid oxide electrolyzer to form H_2 and CO. The gas mixture is then sent to a methane former, and the produced methane is injected into the gas network [37; 38; 39].

Status: unknown, schedule 2011 – 2014

Companies involved: CEA (The Alternative Energies and Atomic Energy Agency), ARMINES, GEG (Gas Electricité de Grenoble), INERIS (National competence centre for Industrial Safety and Environmental Protection), Saipem S.p.A., University of Strasbourg

4.3.9 France: Jupiter 1000

Located at the Fos sur Mer harbour near Marseille, this plant will use renewable energy to produce hydrogen in both PEM and alkaline electrolyzers. Part of the hydrogen will be injected directly into the natural gas network, and part of it will be used in a methanation process, in which it is reacted with captured CO_2 from an industrial flue gas, and the produced methane is then injected into the natural gas grid. The input powers of the electrolyzers are 0.5 MW each. The project will be a platform dedicated for demonstrations devoted to the Energy Transition and to introduce this technology in large scale in France [40].

Figure 6: Designed layout of the Jupiter 1000 plant [40].

Status: in planning, schedule 2014 – 2020

Project partners: GRTgaz, ATMOSTAT SA, CEA (The Alternative Energies and Atomic Energy Agency), CNR (Compagnie Nationale du Rhône), Leroux & Lotz Technologies, Port de Marseille Fos, McPhy Energy SA, TIGF (Transport et Infrastructures Gaz France

SA), the European Union, the French Government, Provence-Alpes-Côte d'Azur regional council

4.3.10 Iceland: ECTOS

In the ECTOS (Economic City Transport System) project three fuel cell buses were used in the public transport system of Reykjavik. A hydrogen station for the vehicles was built which produced, stored and dispensed the hydrogen. The hydrogen is made from water using power from the national grid, which is 100 % renewably produced (geothermal and hydro power). The hydrogen output capacity is adjustable from 10 to 65 Nm^3/h depending on the momentary demand for hydrogen. The project was a success, and the use of the buses and the station was prolonged with the following HyFLEET:CUTE –project [92; 93; 94].

Status: completed, schedule 2001 – 2005

Project partners: Icelandic New Energy Ltd.

4.3.11 Iceland: George Olah Plant

The George Olah plant is built by Carbon Recycling International near Svartsengi geothermal power station. The plant produces renewable methanol using the *Emission to Liquid*-technology developed by the Carbon Recycling International. The reaction in which the renewable methanol is produced is described in equation 4.2.

$$CO_2 + O_2 + 2\,H_2 \rightarrow CH_3OH + 1.5\,O_2 \qquad (4.2)$$

The oxygen and hydrogen in the left side of the equation are produced via electrolysis using renewably produced grid power. The carbon dioxide is extracted from the emissions of the nearby Svartsengi power plant. The product methanol is blended with gasoline and used as a vehicle fuel in Iceland and abroad. The initial production rate is around two million liters of methanol per annum, and Carbon Recycling International has plans to expand the plant's production to over five million liters [95; 96; 97].

Status: operational since 2011.

Project partners: Carbon Recycling International Inc., HS Orka hf

4.3.12 Italy: INGRID

The INGRID is a large scale project to demonstrate the use of solid-state hydrogen storage for power supply and demand balancing. An electrolyzer of 1 152 kW uses excess electricity from wind turbines to split water into hydrogen and oxygen. The main innovation of the project is the modular Hydrogen Solid Storage, in which the hydrogen is absorbed in magnesium hydride without the need for gas compression. The Hydrogen Solid State is directly connected to a 120 kW fuel cell system, which on demand will de-absorb the hydrogen gas and produce electricity. The hydrogen can also be dispensed to different green-hydrogen merchants in movable solid state tanks, to be used for example in power generation, vehicles and hydrogen enrichment of natural gas. The project aims the overall efficiency of the energy storing system to be 50-60 % and the solid state storage is expected to have the energy density up to 600 kWh/m^3. Without the need for compression of the hydrogen gas, safety of the facility is considered to be higher than a traditional gaseous hydrogen storage.

The second objective of this project is the design and development of different tools for smart grid management and monitoring. Tools for simulation, energy management and ICT platforms are studied and experimented [98; 99].

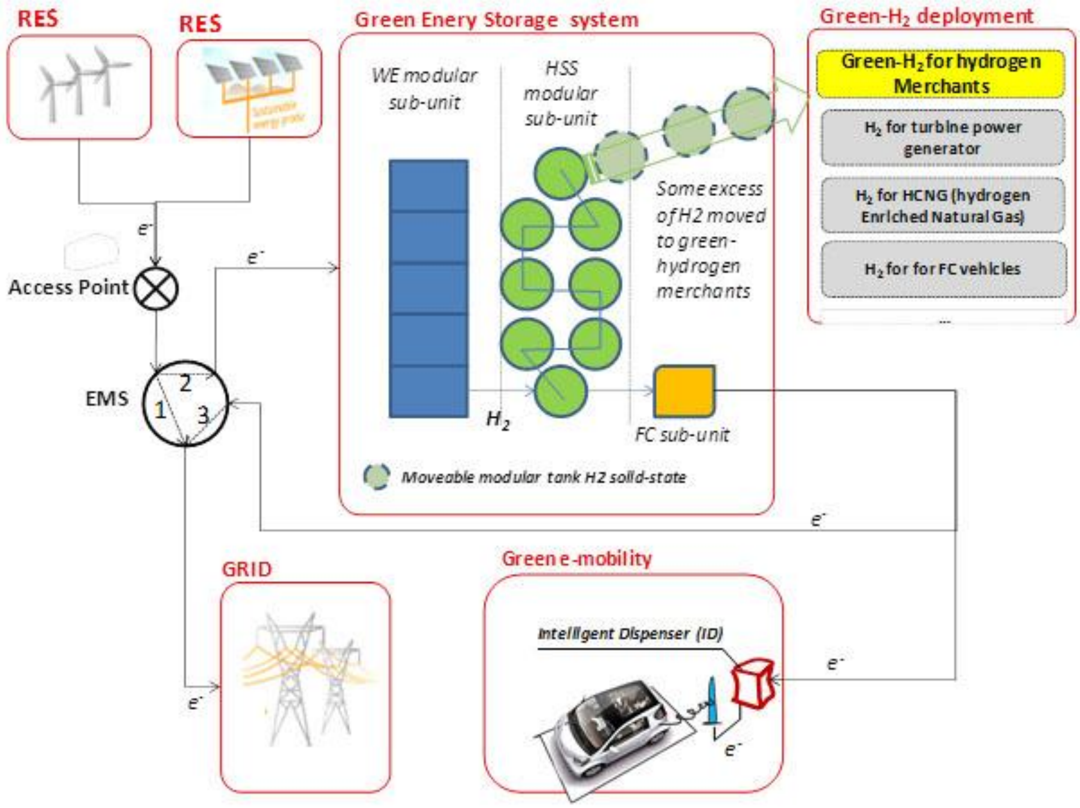

Figure 19: The concept of the INGRID project [98].

Status: active, schedule 07/2012-06/2016

Project partners: Engineering Group, McPhy Energy SA, Hydrogenics, TECNALIA, RSE (Ricerra sul Sistema Energetico), Enel Distribuzione, ARTI (Apulia Regional Agency for Technology and Innovation), Studio Tecnico BFP, European Community

4.3.13 Norway: Utsira

A demonstration project of a self-sufficient society based on wind energy and hydrogen storage was built on the island of Utsira, Norway. Ten private households are the end users of the energy distribution system. The electricity is produced with two wind turbines of 600 kW each. An electrolyzer with the input of 48 kW and production rate of 10 Nm^3/h produces hydrogen gas from the excess electricity. The storage capacity for hydrogen is 2400 Nm^3 at 200 bar. In time of power deficit, the hydrogen is converted back to electricity via a 10 kW fuel cell and a 55 kW hydrogen combustion engine. There is also a system of flywheel, battery and synchronous electric motor to balance the fluctuations of the local grid. The island is connected to the national power grid via a sea cable, providing power for the part of the island that is not part of this project, and backup power for the project grid as well.

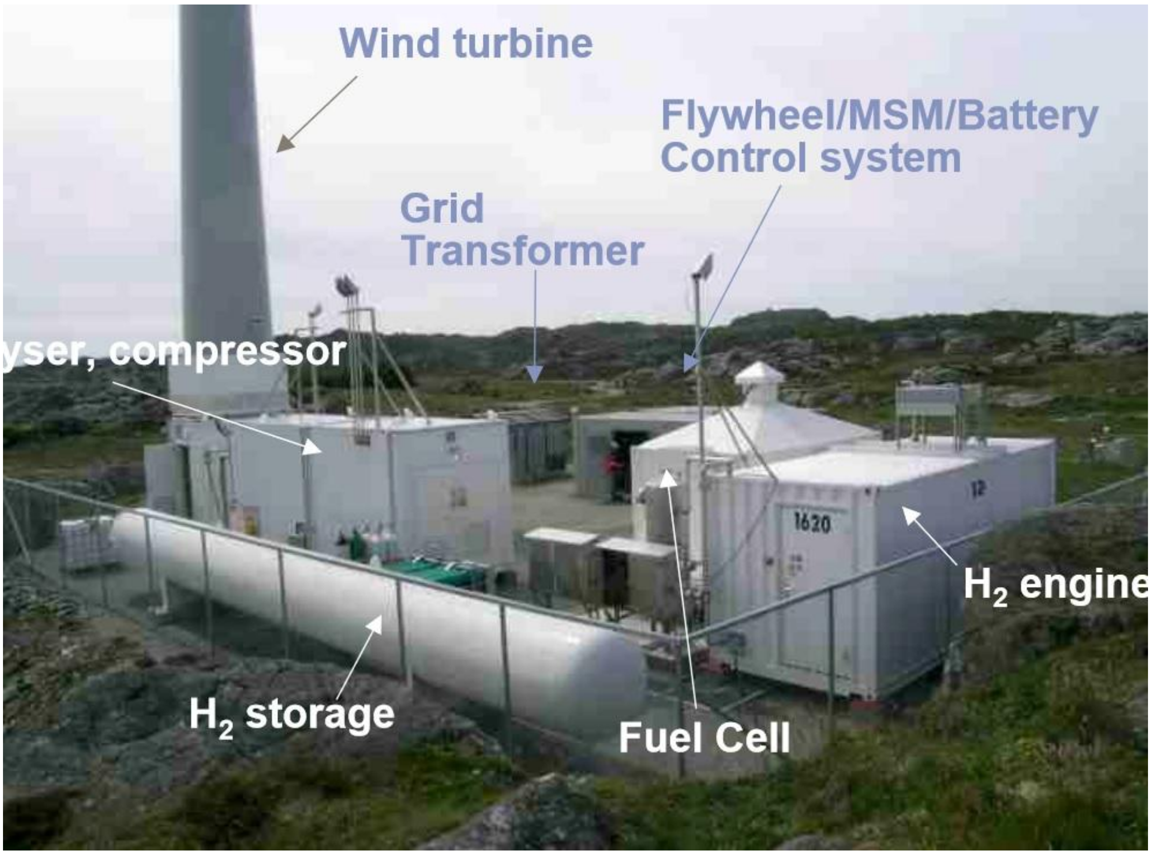

Figure 22: The main components of the Utsira wind-hydrogen system [104].

It was concluded that the technology was not commercially competitive with conventional diesel or combined diesel and wind power supply in remote area applications at the time of completing the project. The project itself was successful, and the consortium made plans of following projects of larger scale [104; 105].

Status: operational since 2004.

Project partners: Hydro ASA, Enercon GmbH, Enova SF, NFR (The Research Council of Norway), SFT (The Norwegian Pollution Control Authority)

4.3.14 Spain: Sotavento

The project is located at the Sotavento Experimental Wind Farm. The excess electricity of wind turbines is used in an alkaline electrolyzer with the capacity of 60 Nm^3/h. The hydrogen is compressed up to 200 bar and stored in site, and the oxygen is released into the atmosphere. The hydrogen fuel is converted back to electricity by a motor-generator of 55 kW.

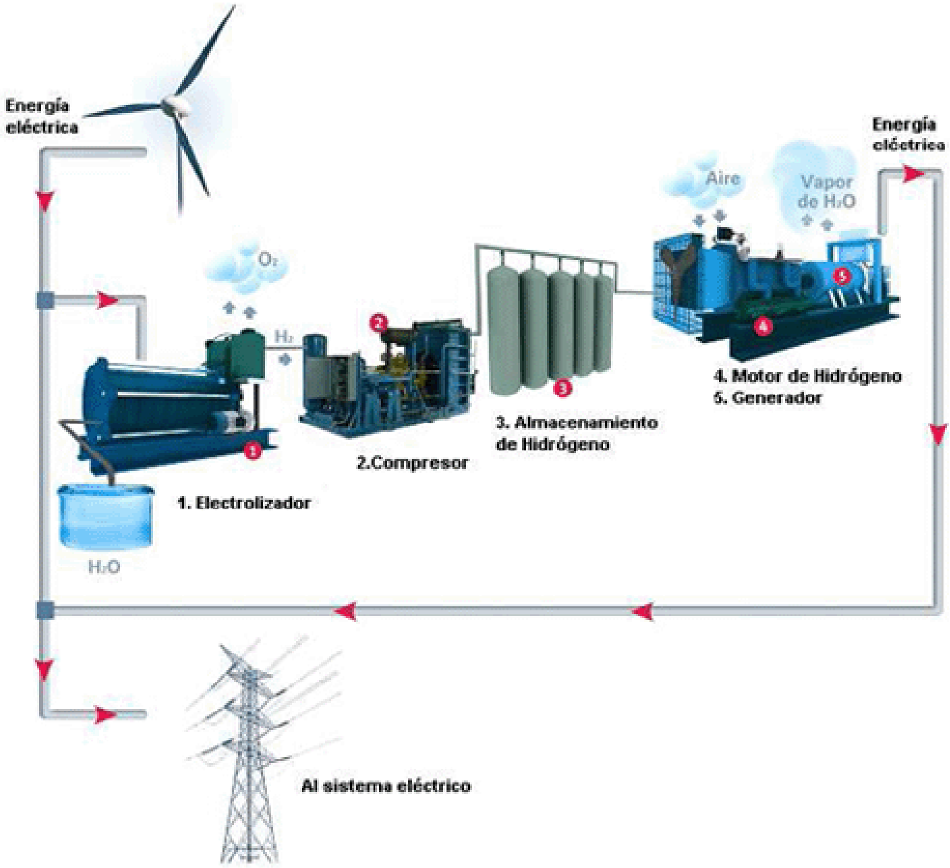

Figure 23: The system of the Sotavento project [106].

The facility has successfully been operated with the aim to balance the deviations from the wind farms predicted production. The facility has also been operated under different technical and economical objectives. The hydrogen is produced at a competitive price for different uses of hydrogen fuel [106; 107].

Status: operational, schedule 2009 – 2011

Project partners: Gas Natural SDG, S.A., Sotavento Galicia, S.A., Galician Ministry for Economy and Industry

4.3.15 Spain: ITHER

The ITHER project (Technology Infrastructure for Hydrogen and Renewable Energies) is located in Walqa Technology Park in Huesca. The electric power of the installation is produced by a 635 kW wind farm and a 100 kW grid of solar panels. The facility is interconnected with the electrical grid. Hydrogen is produced from water with a large scale alkaline electrolyzer and is stored on site in both low and high pressures. The hydrogen is dispensed in a hydrogen station for hydrogen-powered vehicles and fuel cell buses. The installations are considered as test bench facilities, and are accessible to researchers by collaboration agreements [108].

Status: operational, completed in 2010

Project partners: Aragon Hydrogen Foundation

4.3.16 Spain: Hidrólica

Located in the El Gallego windpark of 80 MW in Tahivilla municipality, the project analyses the behavior of the equipment in a power to gas –process. Part of the electricity of a variable-speed wind turbine is used by the PEM electrolyzer of 60 kW. The hydrogen produced is stored in two tanks of 15 and 200 bar. A PEM fuel cell of 12 kW converts stored hydrogen back to electricity [109, p. 219; 110].

Status: unknown, project started in 2007

Project partners: Endesa, S.A., Green Power Technologies, AICIA (Andalusian Association for Research and Industrial Cooperation), INERCO, Besel, S.A.

4.3.17 Spain: El Tubo

This demonstration project is located at Palmas Atlas campus of Loyola University of Andalusia. Electricity from solar panels is used in electrolyzers made by Italian ACTA. The produced hydrogen is stored in metal hydride cartridges and converted back to electricity in a Ballard fuel fell when needed. The installation is visited by students, researchers and potential customers [111; 112; 113].

Figure 24: El Tubo installation [111].

Status: completed, operational

Project partners: Abengoa S.A., ACTA S.p.A., Loyola University of Andalusia, Ballard

4.3.18 Spain: CUTE and HyFLEET:CUTE

As explained previously, the HyFLEET:CUTE was a project in which the use of hydrogen powered fleets of buses were demonstrated in public transport systems. In Barcelona, a 400 kW alkaline electrolyzer used electricity from on-site photovoltaic panels and from the grid to produce hydrogen with the capacity of 60 Nm^3/h. A fleet of three buses was operated by TMB, the public transit operator of Barcelona [42; 114].

Status: completed, 2006 – 2009

Project partners: TMB (Transports Metropolitans de Barcelona), Linde AG, BP plc (British Petroleum), European Commission

4.3.19 Sweden: CUTE

CUTE (Clean Urban Transport for Europe) was a project co-funded by the European Commission with the aim to demonstrate emission-free and low-noise transport systems. Storstockholms Lokaltrafik (Stockholm Public Transport) operated three fuel cell buses. The hydrogen was produced on-site with an alkaline electrolyzer of 400 kW of input power. The power was certified green electricity [42; 115].

Status: completed, 2003 – 2006

Project partners: Storstockholms Lokaltrafik AB, Hydrogenics, Fortum Oy, European Commission

4.3.20 Switzerland: Rapperswil

A pilot plant producing methane from photovoltaic power was built at the University of Applied Sciences in Rapperswil. As the research in Switzerland is strongly focused on solar-thermal production of renewable fuels, this plant is the first power to gas –project in the country. A photovoltaic system of 7.4 kWe is connected to an electrolyzer which produces hydrogen gas. The product gas is fed into a reactor where it reacts with carbon dioxide and forms methane gas and water. The methane is used in natural gas powered vehicles, the production rate of the facility equals to about 36 tankfuls in a month [116; 117; 118].

Status: operational since 2015

Project partners: University of Applied Sciences Rapperswil (HSR), Ergas Obersee AG, ETOGAS GmbH, IBC SOLAR AG, ch-Solar AG, Audi AG, Erdgas Regio AG, Rapperswil-Jona power station, Climeworks AG, Swiss Gas Industry Association (VSG)

4.3.21 The Netherlands: Ameland

This project demonstrated how added hydrogen in a natural gas network affects the grid and devices attached to it. A separate gas distribution grid consisting of PVC, PE and steel was built to provide fuel for fourteen houses, particularly to their central-heating boilers and cookers. The hydrogen was produced using the power of a nearby array of solar panels, and it was injected in the local gas grid. The percentage of hydrogen was gradually increased to up to 20 %. It was concluded that the added hydrogen did not have a noticeable influence neither on the materials of the pipelines nor the behavior and efficiency of the gas-fuelled devices. The project partners and researchers recommended larger scale and longer lasting projects of this kind, possibly with other kind of installations, like industrial ones [119; 120].

Status: completed, schedule 2009 – 2012

Project partners: Stedin Netbeheer B.V., Joulz B.V., N.V. Nederlandse Gasunie, GasTerra B.V.

4.3.22 The Netherlands: Delfzijl

This large-scale plant will use electric power to produce hydrogen and oxygen via electrolysis. The oxygen is used at an adjoining gasification plant, where biomass is gasified to produce syngas. The hydrogen and the syngas are used as raw materials for the chemical industry. Power input of the facility is planned to be 12 MW [121; 122].

Status: planned, schedule 2014 – 2016

Project partners: Torrgas Nederland B.V., Siemens AG, Stedin Netbeheer B.V., N.V. Nederlandse Gasunie, A.Hak Industrial Services B.V., Hanze University of Applied Sciences, Energy Valley Foundation

4.3.23 The Netherlands: Rozenburg

Power to gas demonstration project in Rozenburg includes a complex of thirty apartments that produce natural gas-quality methane from excess renewable electricity. The product gas is injected to an existing natural gas grid. In the project it is demonstrated how a small-scale power to gas production is possible, and how private consumers and homeowners can become more energy independent via decentralized energy generation. The electrolyzer used is in this project a polymer electrolyte membrane (PEM) with electrical input of 7 kW. Maximum hydrogen output is 1.1 Nm³/h with 13.8 bar. Methane is formed catalytically via the Sabatier reaction [124; 125; 126; 127].

Status: active, schedule 2013 – 2018

Project partners: Stedin Netbeheer B.V., DNV GL, TKI Gas, Ressort Wonen, Rotterdam Council

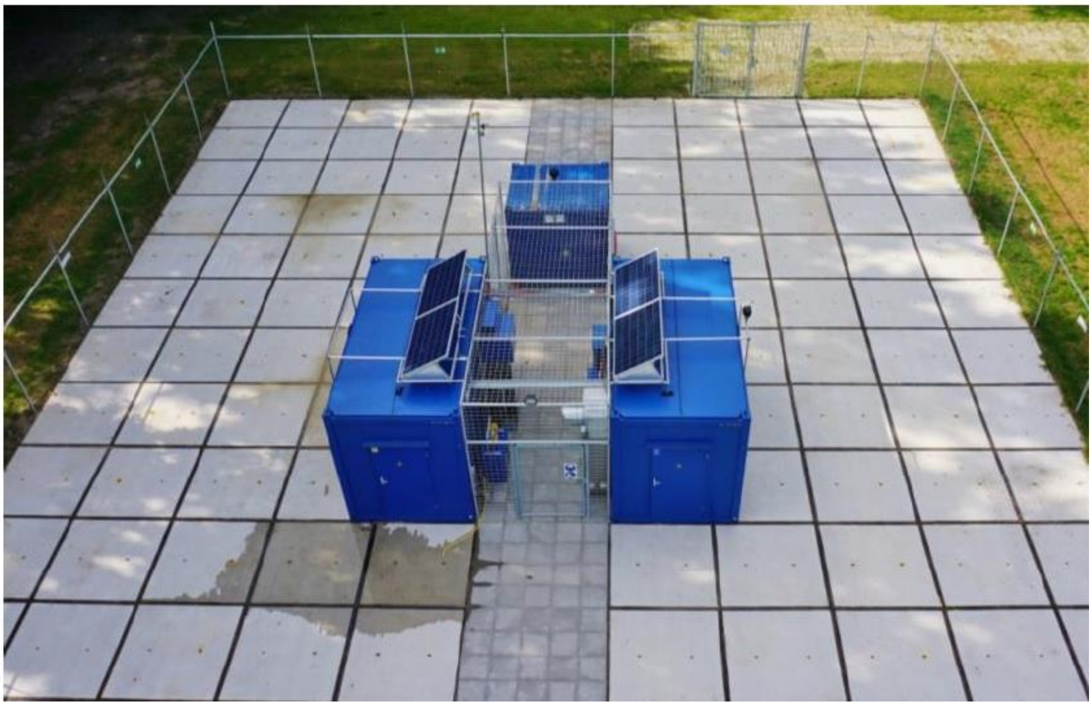

Figure 25: The methane production system in Rozenburg [123].

4.3.24 The Netherlands: HyFLEET:CUTE

The HyFLEET:CUTE was a project that was supported by the European Commission's 6th Framework Research Programme. In the project fleets of hydrogen buses, both fuel cell and internal combustion driven, were being tested in public transportation systems of nine cities around the world. In four cities the hydrogen was produced electrolytically from water. Amsterdam was one of the cities of the project using renewably produced hydrogen with the electricity from a windmill park in the North Sea. The capacity of the alkaline electrolyzer was 60Nm^3/h, with the electric input being 400 kW. The municipal transport company of Amsterdam ran three fuel cell buses for four years, extending the original schedule by one year [42; 128].

Status: completed, 2003-2009

Project partners: Gemeentelijk Vervoerbedrijf (GVB), Shell, N.V. Nuon Energy, Linde AG, Hoek Loos N.V., European Union

4.3.25 United Kingdom: HARI Project

Hydrogen and renewable integration (HARI) project is located at West Beacon Farm in Leichestershire. The project tested the feasibility of a stand-alone energy system based on renewable energy and hydrogen storage. The renewable energy supply consists of two 25 kW wind turbines, 13 kW photovoltaic arrays and 3.05 kW of hydropower. The hydrogen is produced in a high-pressure alkaline electrolyzer with power input of 36 kW. To conserve electrolyzer’s lifetime, which is threatened by the fluctuation of the electrical input, a 2 kW sodium nickel chloride (NaNiCl) battery is connected to system for short-term energy storage and to smooth the fluctuations of the power input. Hydrogen gas is stored in pressurized containers in maximum pressure of 137 bar. The maximum storage capacity is 3 800 kWh of electricity, equivalent of three weeks of the farm’s power consumption. The system includes two proton exchange membrane (PEM) fuel cells. One fuel cell provides combined heat and power (CHP) production, with 2 kW of electricity and 2 kW of heat. The other fuel cell produces solely electric power of 5 kW.

Figure 26: The hydrogen storage of HARI project [129].

The project demonstrated successfully that energy self-sufficiency could be achieved with integrated renewable energy and hydrogen system, even in an off-grid situation. It was concluded that the overall maturity of the technology was not sufficient for larger scale utilization at that time, mainly energy efficiency needed to improve and costs to reduce [129; 130].

Status: completed, schedule 2001 – 2007

Project partners: Loughborough University, Bryte Energy Ltd

4.3.26 United Kingdom: Hydrogen Mini Grid System

A local energy system was built for Environmental Energy Technology Center (EETC) in Rotherham. The primary source of power is a 229 kW wind turbine which supplies the EETC facility with electricity. Excess power is either fed to the electricity grid or used in an electrolyzer, which produces hydrogen gas. The site is capable of storing 200 kg of compressed hydrogen gas. The gas is dispensed via a hydrogen vehicle refueling station. There is also a 36 kW fuel cell system, which provides electricity for the facility in times of low wind power production. In the case of low hydrogen level and electricity deficit, the system has the option for automatically switch to use grid power. When the hydrogen production exceeds the storage and consumption, excess hydrogen is fed into the national gas grid.

Figure 27: Hydrogen fueling station and wind turbine of the facility [131].

The facility is located near the M1 motorway, which is mentioned in the UK H_2Mobility project as a key route for building new hydrogen filling stations for vehicles [131; 132].

Status: operational

Project partners: ITM Power plc, Advanced Manufacturing Park, Sheffield University, DeMontfort University, UPS Systems plc, Rotherham Metropolitan Borough Council, Innovate UK

4.4 North America

4.4.1 USA: Schatz Solar Hydrogen Project

The project was a local solar power system powering an air compressor of aquaria at Humboldt State University’s Telonicher Marine Laboratory in Trinidad, California. A 7 kW photovoltaic array produced electric power to the air compressor, and excess power was fed to an electrolyzer with maximum input power of 6 kW. The electrolyzer produced hydrogen with maximum output of 1.2 Nm^3/h at 6.9 bar, and the hydrogen was stored on site. During nights and cloudy weather, when solar energy was not available, the system switched to fuel cell operation and produced electricity from the stored hydrogen via a 1.5 kW PEM fuel cell. In 2011 the system was rebuilt with a grid-tie inverter, and any excess power of what was consumed was fed into the local utility grid [133].

Status: decommissioned in 2012, began operating in 1991, rebuilt in 2006 and 2011

Project partners: Schatz Energy Research Center, Humboldt State University (part of California State University system)

4.4.2 USA: Wind2H2

The wind-to-hydrogen (Wind2H2) demonstration project is located at the National Wind Technology Center near Boulder, Colorado. The electric power from wind turbines and photovoltaic arrays is fed to electrolyzers, and the hydrogen produced is stored at the on-site hydrogen fueling station or during peak demand hours converted back to electricity via internal combustion engine or fuel cell. The aim of the project is to improve the efficiency of the system in quantities large enough and at adequately low costs to compete with traditional fossil energy sources.

The two wind turbines of the system are both variable speed type, the larger 100 kW turbine has an onboard DC rectifier and the smaller 10 kW turbine has a wind-to-electrolyzer electronics specially designed for this project to convert its wild AC suitable for the electrolyzer input. Different electrolyzer technologies are used via two 40 kW PEM elecrolyzers and one 33 kW alkaline electrolyzer. The PEM stacks showed a decay rate of 9.5 µV/cell-h in the first 2 000 hours of constant power data [134; 135].

Status: unknown, schedule 2003 – 2014

Project partners: NREL (National Renewable Energy Laboratory), Xcel Energy Inc., Proton OnSite, Giner Inc., DOE Wind/Hydro Program (Department of Energy)

4.5 South America

4.5.1 Argentina: Chubut

A renewable hydrogen production plant was commissioned in the Chubut Province, Argentina in 2008. The facility built and operated by Hychico has two electrolyzers of 325 kW which have a total production capacity of 120 Nm³/h of hydrogen and 60 Nm³/h of oxygen at 10 bar. An internal combustion generator set with the power of 1.4 MW is located on site, which is specially adapted to run on mixture of natural gas and hydrogen. The highest achieved hydrogen concentrations are up to 42 % and the engines can maintain their maximum output with 27 % of hydrogen in the fuel mixture. The high purity oxygen is sold for industrial customers.

In the first phase of the project, wind resource data was used as the input power to the electrolyzers to simulate an actual wind park. When adjoining wind park was built in 2011, the plant has got its electric power from there. The wind farm consists of seven 0.9 MW wind turbines, total capacity being 6.3 MW. The company also has plans for larger scale hydrogen production and plans on experimenting with underground hydrogen storage and materials for hydrogen containers [22; 23, p. 133].

Status: operational, hydrogen plant commissioned in 2008, the wind park in 2011.

Project partners: Hychico S.A.

4.6 Oceania

4.6.1 New Zealand: HyLink

A small scale pilot project was conducted in a small and remote farming community in Totara Valley, Wairarapa. The project was ran by Indistrial Research Limited (IRL), which is solely owned by The New Zealand Government. A wind turbine of 300 W provided electric power for a 400 W PEM electrolyzer, which produced hydrogen. The gaseous hydrogen was delivered by a 18 mm hydrogen pipeline into a load end two kilometers away, where a PEM electrolyzer of 1 kW produced power and heat and a hydrogen burner of 1 kW produced additional heat. The heat and power load consisted of three farmhouses and various farm buildings. The power input for the electrolyzer was buffered with a battery and the storage capacity of the hydrogen pipeline was 400 liters, which equals to about 5 kWh with the used 4 bar pressure.

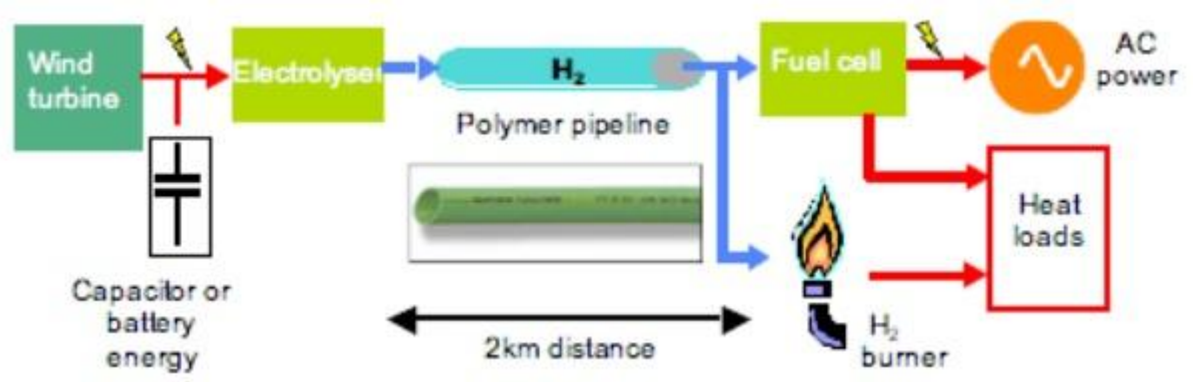

Figure 21: Scheme of the HyLink project [102].

The project demonstrated successfully that hydrogen can be produced from remote wind turbines. The community was grid-connected, but they used as much local energy as possible. The collected energy was smaller than originally expected due to the small size of the turbine and unexpected wind conditions. The costs of the project were considered high, but they are expected to be reduced due to further optimization of the system and maturation of the hydrogen technology.

IRL made plans for succeeding projects, and one system of smaller scale was built in a wildlife reserve in Wellington Harbour in 2013. A small system produces hydrogen from surplus wind and solar power, and it is used in cooking and heating water in one house [102; 103].

Schedule: completed, schedule 2001 – 2005

Project partners: Industrial Research Institute of New Zealand (now Callaghan Innovation)

5 RESULTS

A total of 57 projects were reviewed, a summary of the key features is presented in appendix A. The following examination should not be considered as a comprehensive statistical study, since it doesn’t include all or nearly all of the existing projects, but rather as an overview of recent and well-documented power to gas projects.

The end product is hydrogen in 41 projects, methane in 14 and methanol and other compounds in four projects. As described in section 3.1, hydrogen is an excellent energy carrier and further processing with inevitable efficiency losses should be omitted whenever hydrogen can be used by itself. This is why over 70 % of the projects use hydrogen in their applications.

The most basic case where power to gas concept is applied is in time-shifted electric power generation in the utility grid, this is the case in 18 projects. All of them use hydrogen as a storage media, with the exception of the very first power to gas project in Tohoku, Japan, a small scale research project which demonstrated the complete loop of carbon recycling. All four projects involving isolated power networks used hydrogen.

The integration of electric and gas grids occurs in almost one third of the projects, where product gas is injected into the natural gas grid. Most of these projects (12 out of 18) inject hydrogen into the natural gas grid. No major problems were reported in projects using hydrogen in a mixture in natural gas applications. Even though presented as different applications, several projects both generate electricity and inject product gas into the gas network.

Mobility is the third major application in the reviewed projects. Without two exceptions, all of the projects affiliated with mobility use hydrogen. The exceptions are a methanol production plant in Iceland and a methane production and dispensing facility in Switzerland.

Waste water treatment is present in three projects, all of them produce methane via biological methanation. Biological methanation seems to be very efficient when coupling with waste water treatment, since the oxygen from electrolysis can be recycled in the water treatment process, and the methanation receives a concentrated carbon source.

The end product is utilized by the chemical industry in four projects. Chemical industry uses all mentioned outputs of the processes (hydrogen, methane, methanol and undefined). In spite of relatively small number of projects, it should be noted that the largest plant by input power (Delfzijl, 12 MW_e) is being built for the chemical industry.

All of the projects that produce methane as the end product inject it into the natural gas grid, with the exceptions of one mobility project, one provider for the chemical industry and two research facilities. As some grid operators consider hydrogen as an unwanted impurity, methanation including its added efficiency losses is technically viable when cheap or free surplus electricity is available.

Almost half of the projects are located in Germany. This is partly due to the *Energiewende*, the political decision in Germany of transitioning to completely renewable energy production in the future. The strong political backing is visible in the listings of the project partners, as several projects involve federal, state or local government. Other notable countries are France and Spain with five projects found in each. Worth mentioning are also the Netherlands and especially Denmark, which have four projects each, in spite of the smaller size of the countries compared to the aforementioned three. Denmark has very extensive wind power production, and the balancing of the intermittent production is an important challenge to which the concept of power to gas has been seen as one of the possible answers.

Out of the 57 projects reviewed, only six are located outside of Europe. This is largely due to the fact that there is a strong political backing by the European Commission and the national governments, and that in many regions wind power has been constructed and its penetration in the grid is deep enough to make the balancing of the non-conventional power production viable.

The project located in Hebei, China is especially interesting case, as it is represents the exportation of a full-scale project to a rapidly growing energy market. The hybrid power plant in Prenzlau, Germany which is an model for the upcoming facility in China, can be seen as an archetype for a power to gas –plant with almost complete range of applications. The facility has renewable power production, hydrogen production and storage, on-site CHP production, gas grid injection and dispensing station for hydrogen vehicles. If these types of facilities will become common in China, which undoubtedly has and will have an increasing demand for power production, it would result in less fossil fuel-based power production to be built, and the consequences to the global emissions will be significant.

The project in Ameland, Netherlands is often referenced in later projects. In the project renewably produced hydrogen was injected into a local gas grid, with the hydrogen content reaching up to 20 %. A similar project in larger scale called GRHYD is active in Capelle-la-Grande, France. The adding of electrolytic hydrogen into the natural gas grid will increase the sustainability and reduce the carbon emissions of the gas users. The experiences from these projects are important, for long term effects of hydrogen in natural gas infrastructures and applications are unknown.

In most projects, there is no mention of the oxygen. This presumably means that the oxygen is vented into the atmosphere, as additional compressing and bottling for distribution introduces losses to the overall efficiency as discussed in section 3.7.

As most of the projects reviewed involve electricity production and/or natural gas grid injection, power to gas can be seen strongly as an energy storage and production time shifting solution. Gas powered vehicles have not yet become common, and less than one third of the projects involves mobility. The demand for sustainable vehicle fuels, possibly including gaseous ones, will definitely increase in the near future, but the current state of mobility sector creates no significant need for a large number of new power to gas projects.

6 CONCLUSIONS

The purpose of this thesis work was the screening of power to gas projects worldwide. An introduction to the properties of renewable energy in power grid and alternative energy storage options were given. The business case and application for the end product of each facility was sorted out. The research was done by going through publications, presentations and project web pages.

A fundamental economical feasibility assessment is excluded from this study, but from technical point of view the power to gas is almost ideal way of storing energy. The power to gas concept seems generally feasible in applications where the production of intermittent renewable energy has to be smoothed and time shifted. Most of the projects involved power production to electric power grid and injection of hydrogen or methane into the natural gas grid. Slightly less than one third of the reviewed projects produced fuel for mobility applications. Chemical industry was the end user of the product in a few cases. Hydrogen over methane was favored in over 70 % of the reviewed projects. This is backed by the increased costs, complexity and efficiency losses when the step of methanation is added.

Alkaline electrolysis for hydrogen production and catalytic methanation seem to be the most mature and established methods when converting power to gas. With further development, the PEM technology has the potential of becoming the superior method in hydrogen production because of its ability to operate in dynamical loads. Biological methanation provides high efficiency and ability to operate dynamically, and seems to be a very viable solution in cases where a concentrated source of carbon dioxide is adjoiningly available. Biogas production and waste water treatment plants were coupled with biological methanation in a number of cases.

Improvements in efficiency and dynamical operation in both hydrogen and methane production are expected in the near future, making the concept of power to gas even more viable. The concept itself is relatively new and immature, and most of the facilities are referred to as *research, pilot* or *demonstration plants*. In the future when information is gathered from the operation of these now-novel plants, succeeding installations and applications will have a solid foundation. Prominent worldwide increasing of the renewable energy production is inevitable, and power to gas is one of the best, if not the best concept to handle the intermittency related to it.

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APPENDIX A. Summary of the key features of the reviewed projects.

Project name	**Country**	**Product**	**Electrolysis method**	**Methanation method**	**Input power [kW$_e$]**	**Application**	**Schedule**
Hebei	China	hydrogen	alkaline	n/a	4 000	-	planned
Tohoku	Japan	methane	alkaline	catalytic	-	research, electric power generation	built in 1995
HyFLEET:CUTE, CUTE	Germany	hydrogen	-	n/a	390	mobility	2003 - 2011
Reussenköge	Germany	hydrogen	PEM	n/a	200	electric power generation	active
Schnackenburgallee	Germany	hydrogen	PEM	n/a	-	mobility	2015 -
HafenCity	Germany	hydrogen	-	n/a	-	mobility	2012 -
Prenzlau	Germany	hydrogen	alkaline	n/a	500	electric power generation, natural gas grid injection	2011 -
Werlte	Germany	methane	-	catalytic	6 300	natural gas grid injection	2013 -
Ibbenbüren	Germany	hydrogen	PEM	n/a	150 [1]	natural gas grid injection	2015 -
H2Herten	Germany	hydrogen	-	n/a	-	electric power generation, mobility	active
CO2RRECT	Germany	methane, methanol	PEM	catalytic	100	chemical industry	2009 - 2014
BioPower2Gas	Germany	methane	PEM	biological	400	natural gas grid injection	2013 - 2016
Frankfurt am Main	Germany	hydrogen	PEM	n/a	325 [2]	natural gas grid injection	2014 - 2016
Energiepark Mainz	Germany	hydrogen	PEM	n/a	3 900 [1]	natural gas grid injection, various	in commission
Stuttgart	Germany	methane	alkaline	-	250	-	2012 -
H2Move	Germany	hydrogen	PEM	n/a	-	mobility	2013 -
Scwandorf	Germany	methane	-	biological	-	-	2014 -
MicroPyros	Germany	methane	-	biological	-	-	2014 - 2017
Hassfurt	Germany	hydrogen	PEM	n/a	2 100	electric power generation, natural gas grid injection	planned
HYPOS	Germany	hydrogen	-	n/a	-	chemical industry, mobility	planned

Power-to-Liquids	Germany	various	SOEC	n/a	-	chemical industry, electric power generation	active
Cottbus	Germany	hydrogen	alkaline, PEM	n/a	-	research, electric power generation	2010 - 2013
WindGas Falkenhagen	Germany	hydrogen	alkaline	n/a	2 000	natural gas grid injection	2013 -
WindGas Hamburg	Germany	hydrogen	PEM	n/a	1 500	natural gas grid injection	2012 - 2016
H2BER	Germany	hydrogen	alkaline	n/a	500	mobility, electric power generation, natural gas grid injection	2014 -
RH2-WKA	Germany	hydrogen	-	n/a	1 000	electric power generation, natural gas grid injection	2009 - 2015
Stralsund	Germany	hydrogen	alkaline	n/a	20	research, electric power generation	active
Foulum	Denmark	methane	n/a	biological	n/a	pre-commercial test	2011 - 2013
BioCat	Denmark	methane	alkaline	biological	1 000	natural gas grid injection	in commission
Vestenkov	Denmark	hydrogen	-	n/a	104	local CHP production	2007 - 2014
MeGa-stoRE	Denmark	methane	alkaline	catalytic	-	biogas upgrading	2013 - 2015
GRHYD	France	hydrogen	-	n/a	-	natural gas grid injection, mobility	2013 - 2020
MYRTE	France	hydrogen	-	n/a	-	isolated power network	2013 -
Minerve	France	various	n/a	n/a	-	various	2014 - 2015
DEMETER	France	methane	SOEC	-	-	natural gas grid injection	2011 - 2014
Jupiter 1000	France	hyrdogen, methane	alkaline, PEM	-	1 000	natural gas grid injection	2012 - 2020
ECTOS	Iceland	hydrogen	-	n/a	-	mobility	2001 - 2005
George Olah	Iceland	methanol	-	n/a	-	mobility	2011 -
INGRID	Italy	hydrogen	-	n/a	1 152	electric power generation, various	2012 - 2016
Utsira	Norway	hydrogen	-	n/a	48	isolated power network	2004 -
Sotavento	Spain	hydrogen	alkaline	n/a	-	electric power generation	2009 - 2011
ITHER	Spain	hydrogen	alkaline	n/a	-	mobility	2010 -

Hidrólica	Spain	hydrogen	PEM	n/a	60	electric power generation	2007 -
El Tubo	Spain	hydrogen	PEM	n/a	2,65	electric power generation	active
HyFLEET:CUTE	Spain	hydrogen	alkaline	n/a	400	mobility	2006 - 2009
CUTE	Sweden	hydrogen	alkaline	n/a	400	mobility	2003 - 2006
Rapperswil	Switzerland	methane	-	-	-	mobility	2015 -
Ameland	The Netherlands	hydrogen	-	n/a	-	natural gas grid injection	2009 - 2012
Delfzijl	The Netherlands	hydrogen	-	n/a	12 000	chemical industry	2014 - 2016
Rozenburg	The Netherlands	methane	PEM	catalytic	7	natural gas grid injection	2013 - 2018
HyFLEET:CUTE	The Netherlands	hydrogen	alkaline	n/a	400	mobility	2003 - 2009
HARI	United Kingdom	hydrogen	alkaline	n/a	36	isolated power network	2001 - 2007
Hydrogen Mini Grid System	United Kingdom	hydrogen	-	n/a	-	mobility, electric power generation, natural gas grid injection	active
Schatz Solar Hydrogen Project	USA	hydrogen	-	n/a	6	electric power generation	1991 - 2012
Wind2H2	USA	hydrogen	alkaline, PEM	n/a	113	electric power generation, mobility	2003 - 2014
Chubut	Argentina	hydrogen	-	n/a	650	electric power generation	2008 -
HyLink	New Zealand	hydrogen	PEM	n/a	0.4	isolated power network	2001 - 2005

[1] nominal capacity
[2] peak capacity

n/a = not applicable
- = information unavailable